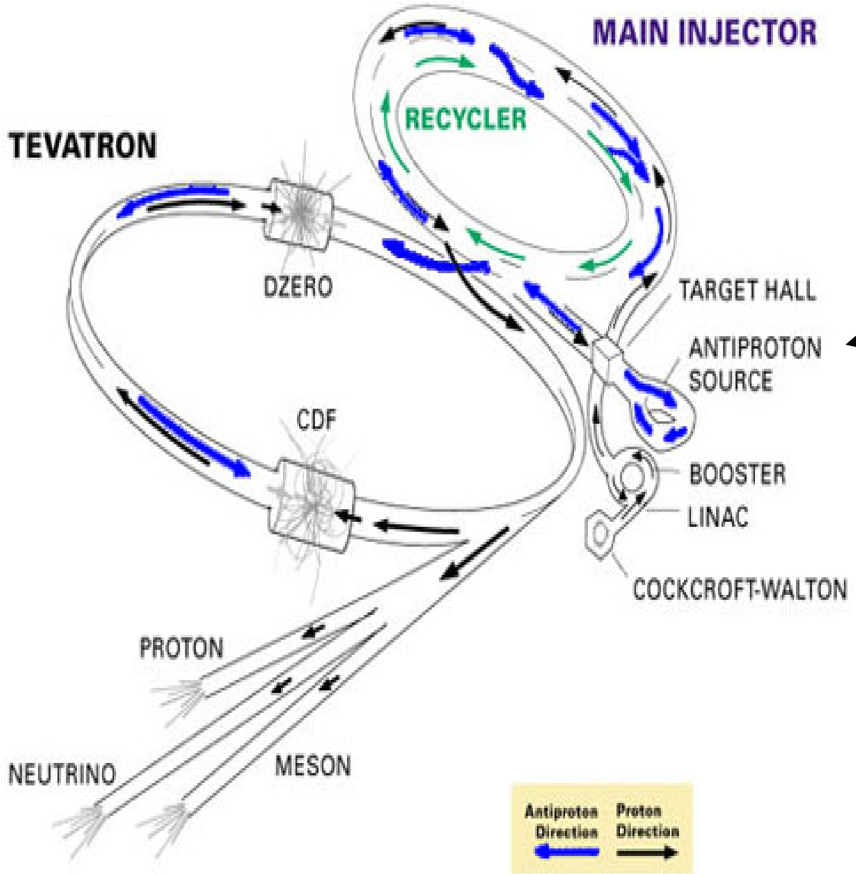
A Brief Historical Look at B Physics using proton anti-proton collisions and selected recent results from Tevatron



$\bar{p}$ source

Nigel Lockyer University of Pennsylvania

50 Years of Anti-protons Anniversary Symposium October 28-29th, 2005
Lawrence Berkeley National Laboratory (LBNL)

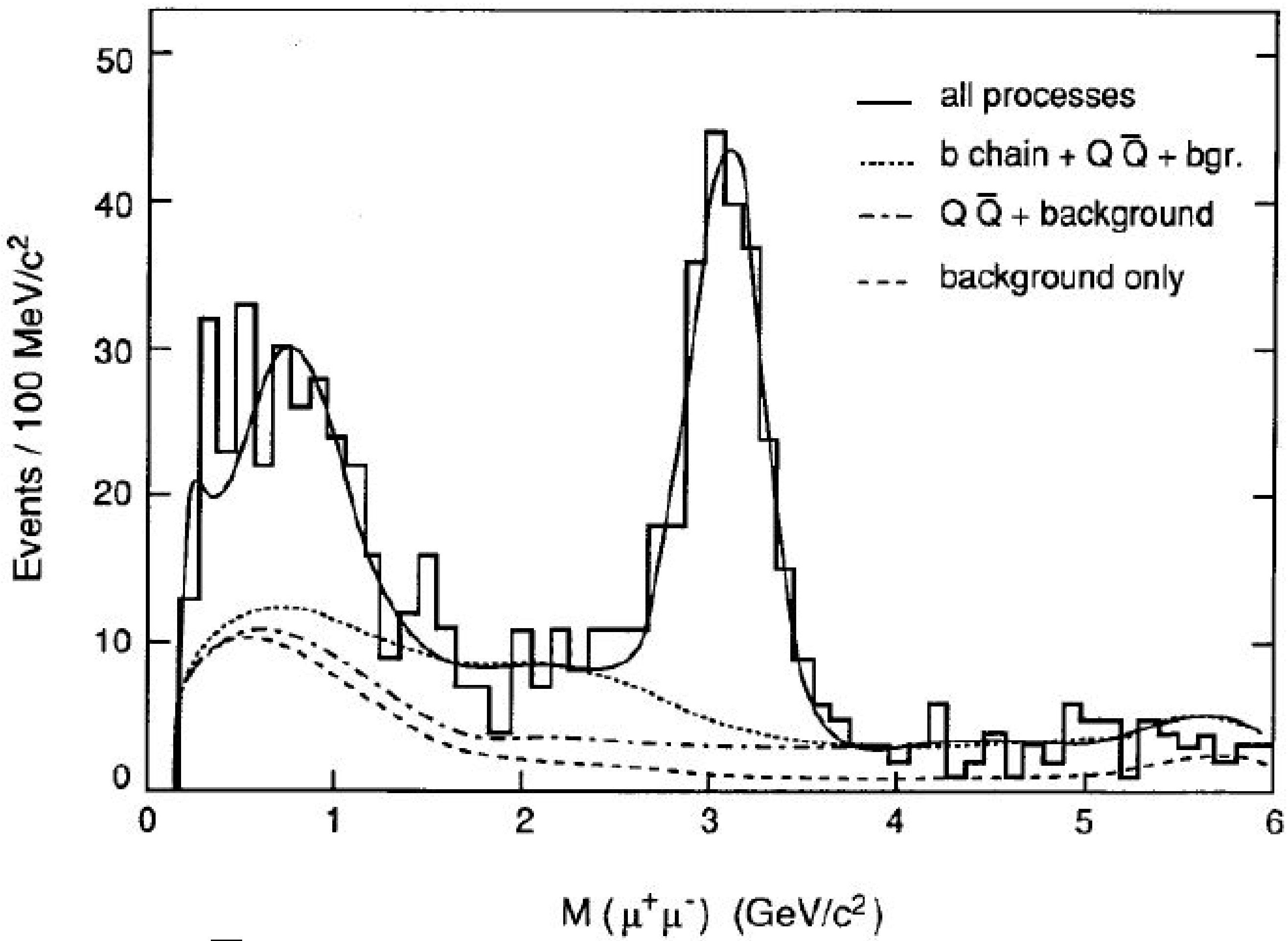
Hadron Colliders are Discovery Machines

But that perception needed to be expanded after the Tevatron

Now “Precision B physics”

UA1 @ CERN

Large Beauty Production at UA1 (J/ψ Clean)



$\sigma(p\bar{p} \to b\bar{b} + X) = 19.3 \pm 7\ (\text{exp}) \pm 9(\text{th})\ \mu b$

Physics Letters B Volume 256 Feb. 28 1991

CDF @ Fermilab
Run1

- First Fully Reconstructed B Meson in Hadron Collider
- First Hint of CP Violation in B System (looked like SM)

First Fully Reconstructed B meson in a proton antiproton Collider-big surprise!

$B \rightarrow J/\psi\ K^+$

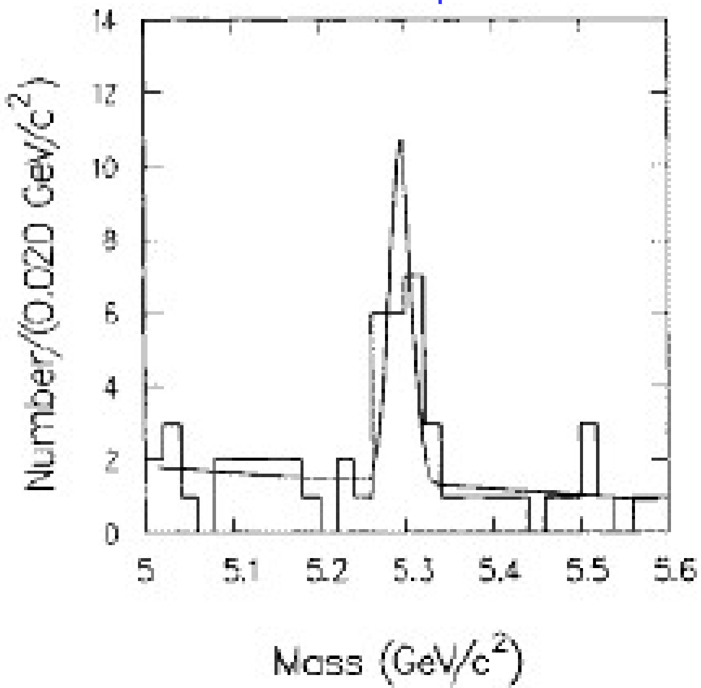


FIG. 2. $\mu^+\mu^-K^\pm$ mass distribution after all cuts. The histogram is the data and the solid curve is a fit by a Gaussian signal (with the width fixed to 0.012 GeV/c^2) plus linear background.

This plot started the big push to do B Physics with Exclusive Decays-goal was to acquire a large sample of $B \rightarrow J/\psi\ K_s$ decays, to do CP violation studies but that proved to be harder

Phys. Rev. Lett. 1992 June 8;68(23):3403

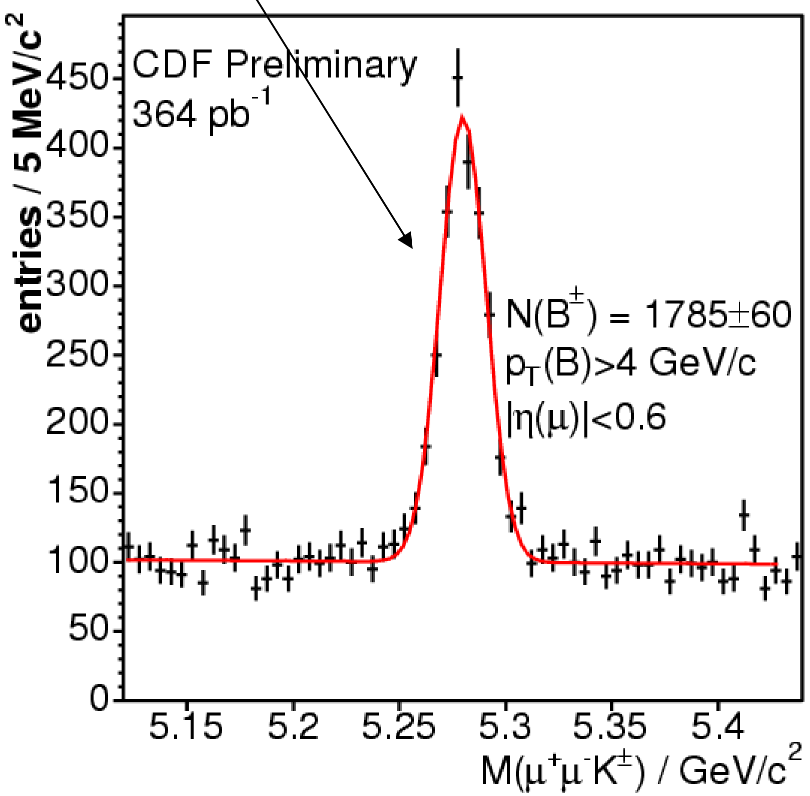
Recorded 2.6 pb^{-1} of data

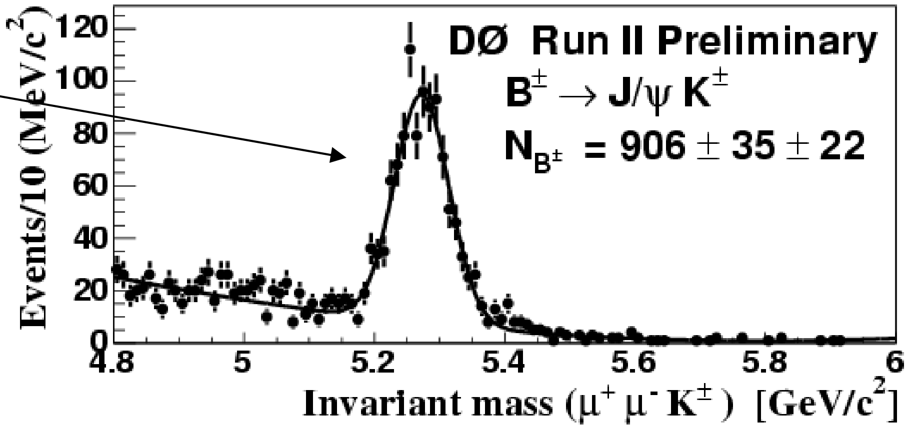
~1000 J/ψ 's & 14 B mesons reconstructed

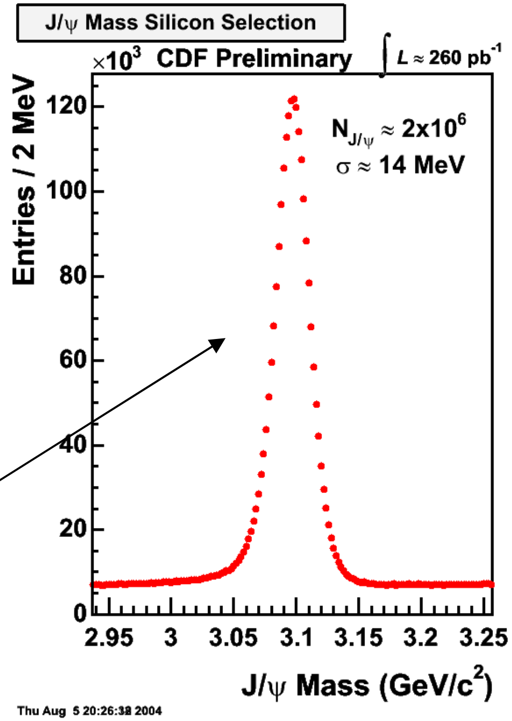
$\sigma(\bar{p}p \text{ -> } bX)$; $P_t > 11.5$ GeV/c $|\eta| < 1 = 6.1 \pm 1.9 \pm 2.4\ \mu b$

CDF & D0 Today

Thousands of Reconstructed B Mesons







Millions of J/ψ mesons

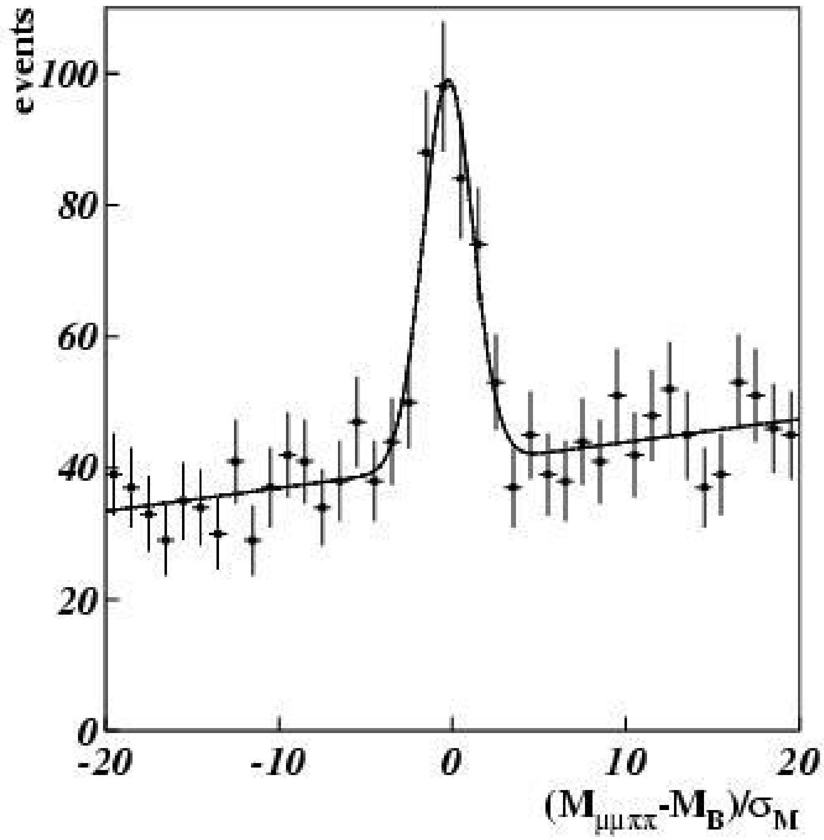
How was this Possible?

- Large B total cross section ~50 μb at Tevatron energies
- Big fraction of total inelastic cross section (~1:1000)
- Soft production (peaked at B mass) and hence small number of additional tracks in event (CLEAN events !)
- Few extra tracks in cone around B meson - another surprise
- Triggered on 3 GeV/c di-muons in central region (thin steel)
- Calorimetry less important initially
- Large precision tracking detectors developed in high B fields
- Long B lifetime led to high precision silicon detectors
- Unfortunately efficiency low, only ~5% events reconstructable
- Zoo of b hadrons: B^0, B^+, B_s, B_c, Λ_b, Ξ_b, B^{**}
- 30% acceptance for “other” B (mixing and CP possible)

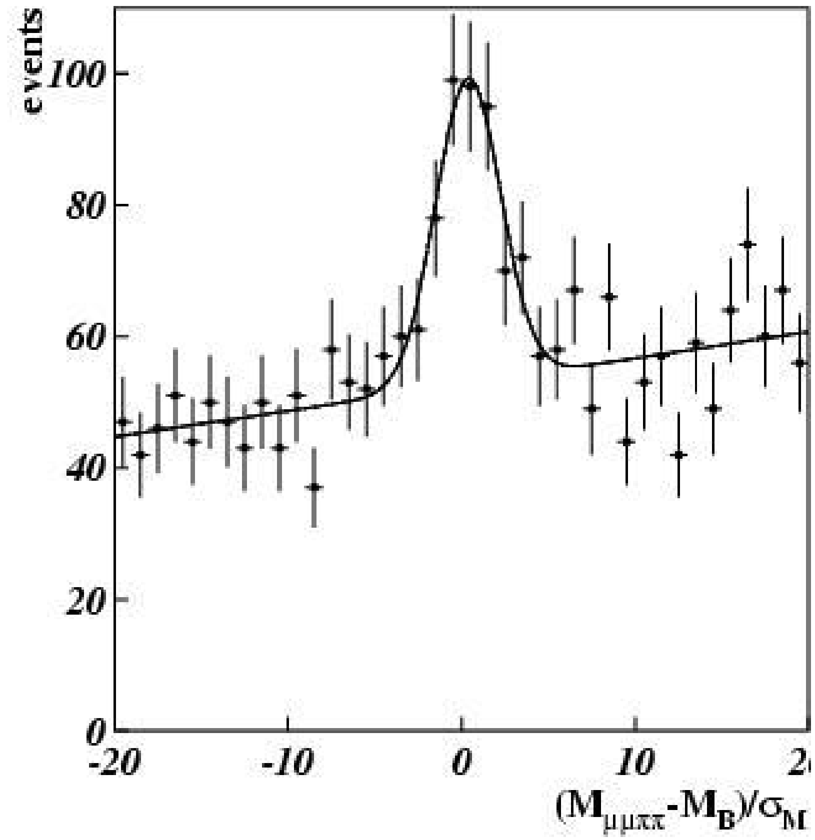
Basics of the CP Violation Measurement

- Reconstruct the CP eigenstate B→J/ψ K_s
- Use the "other B " to identify B or anti-B meson at production
- Three tag techniques used (want high tagging efficiency ε):
  - Soft lepton tag (from mixing analysis)
  - Jet charge tag (from mixing analysis)
  - Same-side tag (from mixing analysis)
- Wrong tags dilute statistical power (hard in hadron machine)
- Parametrized as D=correct tags-incorrect tags/sum
- εD^2 20% in e^+e^- and at best a few percent CDF
- In a hadron collider b-quark pairs are produced as two incoherent meson states
- Lifetime measurements verify distance scale
- Asymmetry can be measured as either a time-dependent (statistically more powerful) or time-integrated quantity.

Large $B \rightarrow J/\psi\ K_s$ Tagged Sample (CP Eigenstate)



Silicon ~200 events

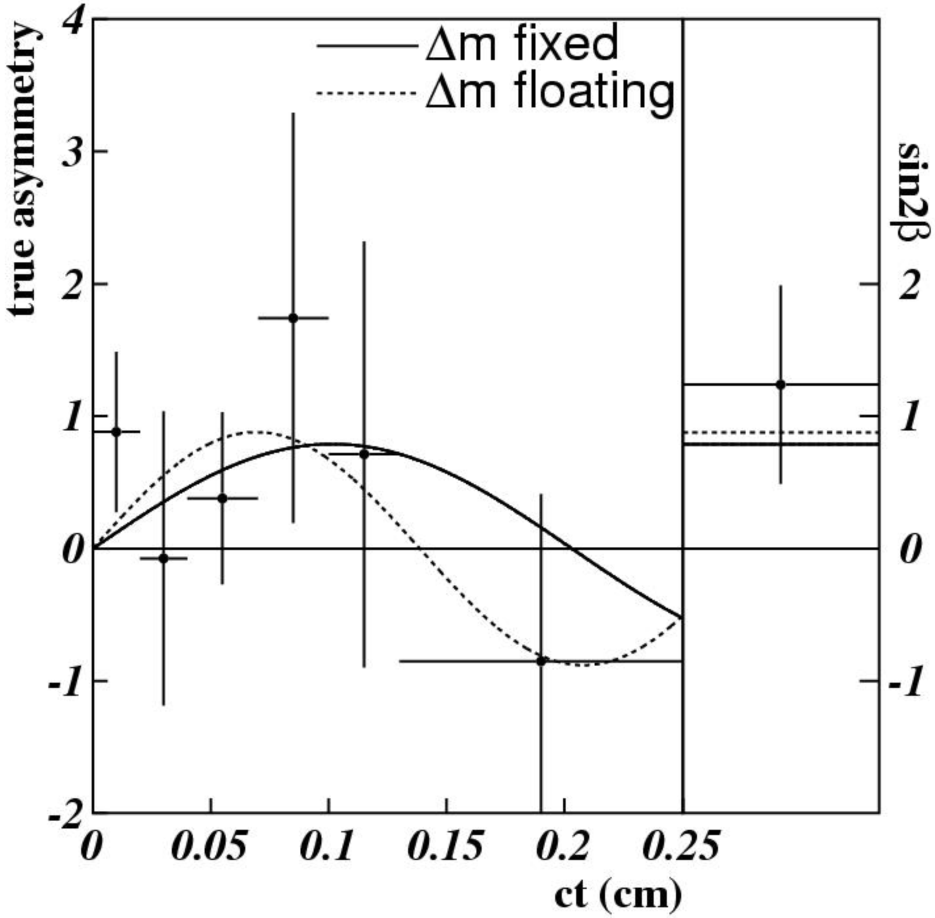


No Silicon~ 200 events

110 pb^{-1} (few percent εD^2)

Phys. Rev. D61 072005(2000)

CDF Sees First Hint of Large CP in B Decays



Sin 2β=0.79 ± 0.39(stat) ± 0.16(syst.)

CDF and D0 @ Fermilab

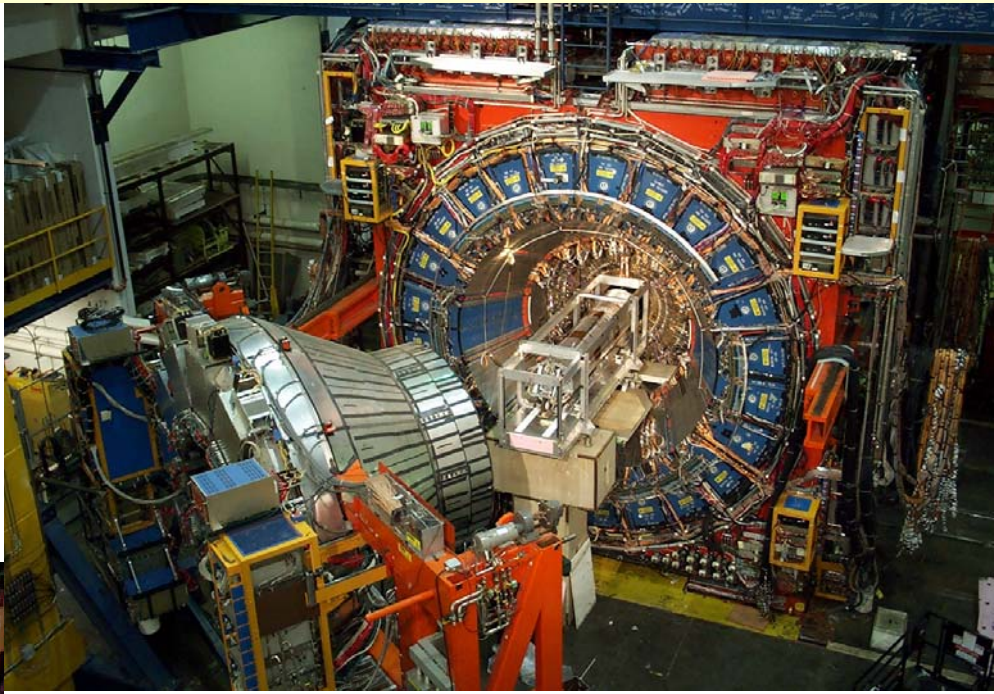
Run II (2001→…)

- Secondary Vertex Trigger (a first)
- B Masses
- B Lifetimes
- Quantum mechanical Mixing
- Flavor changing neutral current decays
- Two body decays

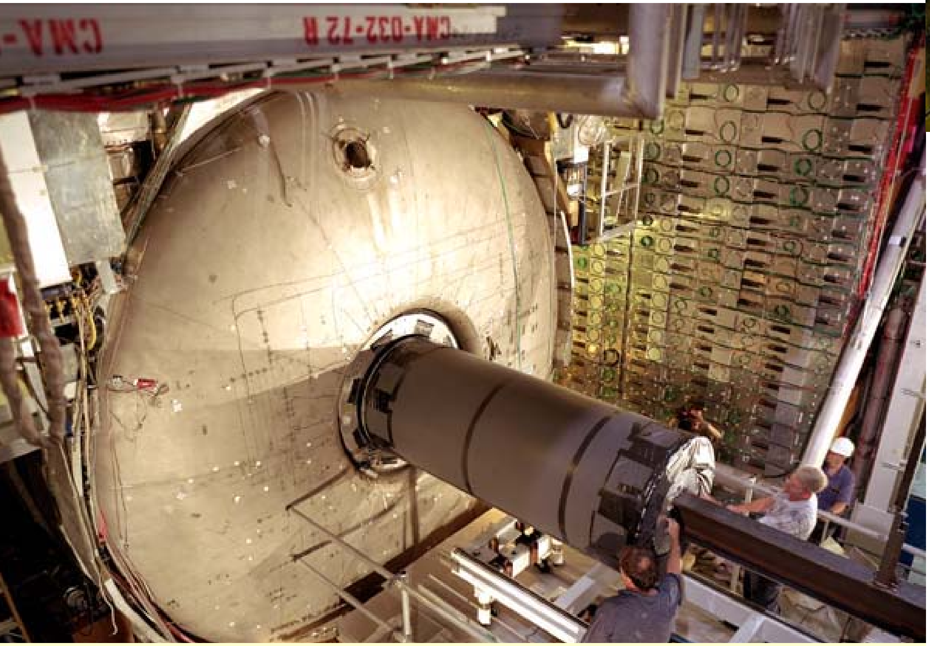
Superb Detectors

- Both detectors
  - Silicon microvertex detectors
  - Central tracking in Solenoid
  - High rate trigger/DAQ system
  - Calorimeter & muon systems
  - Require all-charged final states

CDF silicon detector installation

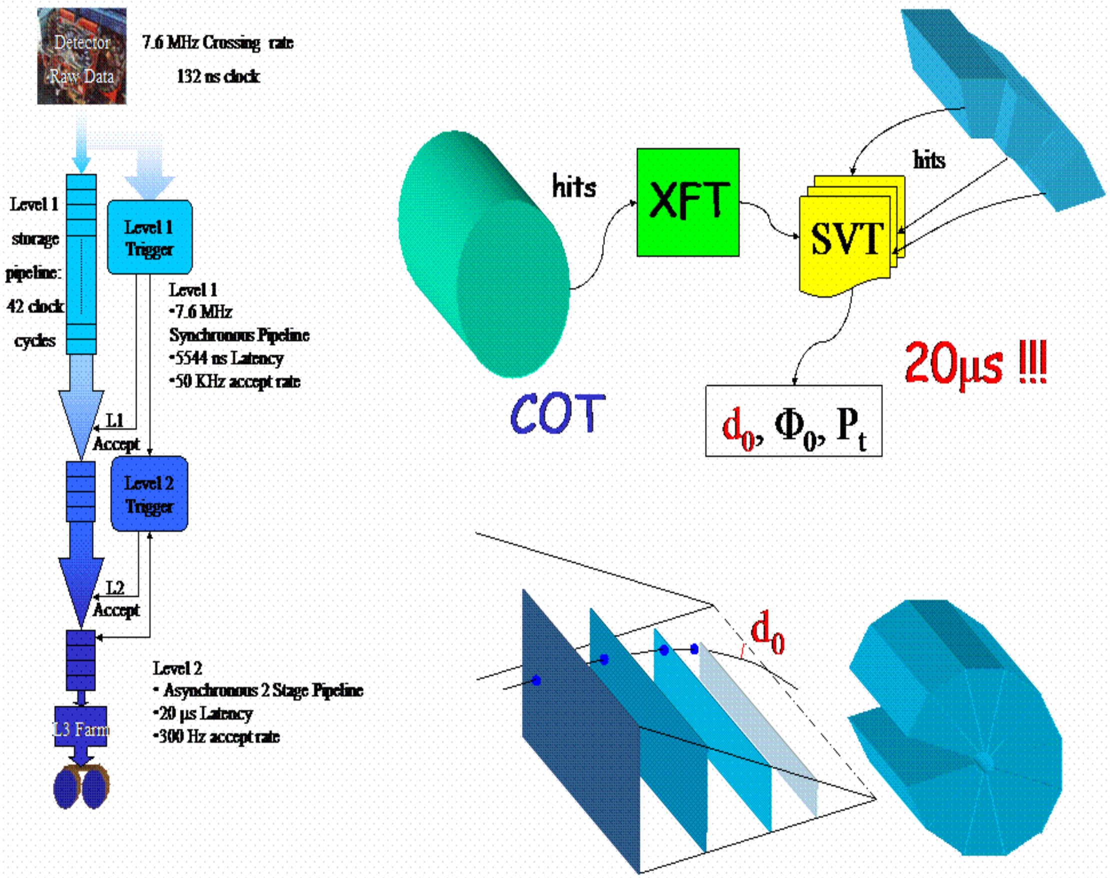


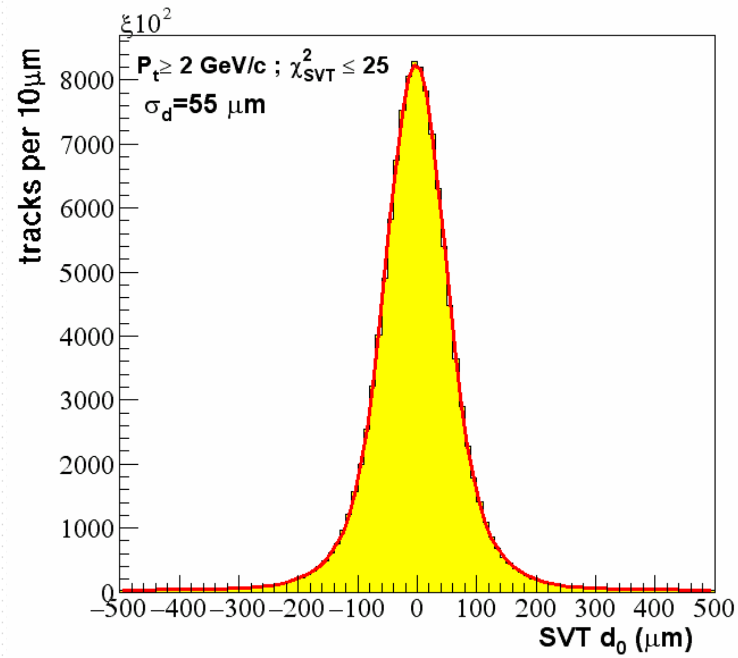
- DØ
  - Excellent muon ID & coverage
  - Excellent tracking acceptance
- CDF
  - Particle ID (TOF and dE/dx)
  - Excellent central tracking mass resolution
  - Dedicated secondary vertex trigger



DØ fiber tracker installation

Silicon Vertex Trigger (CDF)



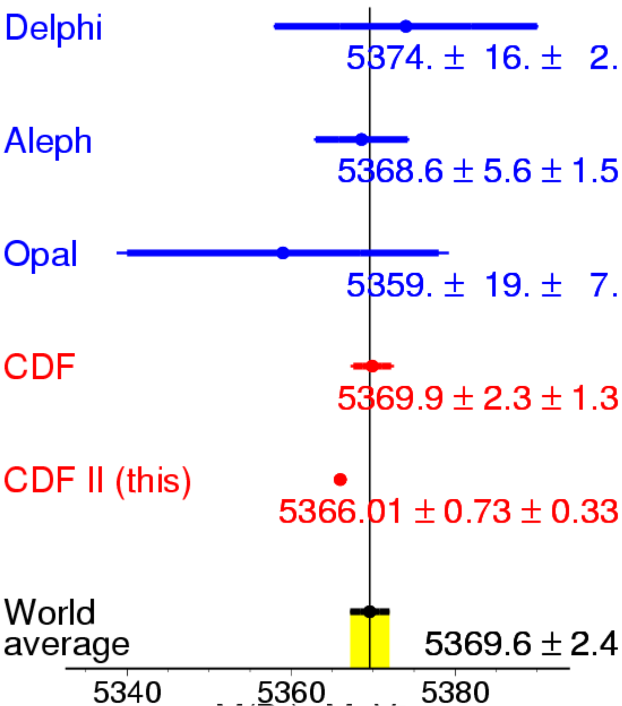


Impact Parameter Resolution (35 ⊕ 33) μm SVT ⊕ beam

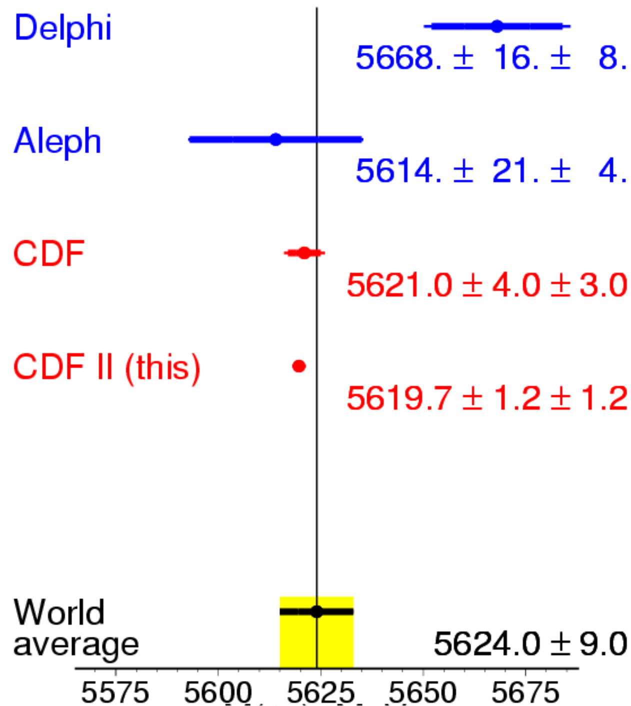
⇒ σ = 48μm

b hadron masses

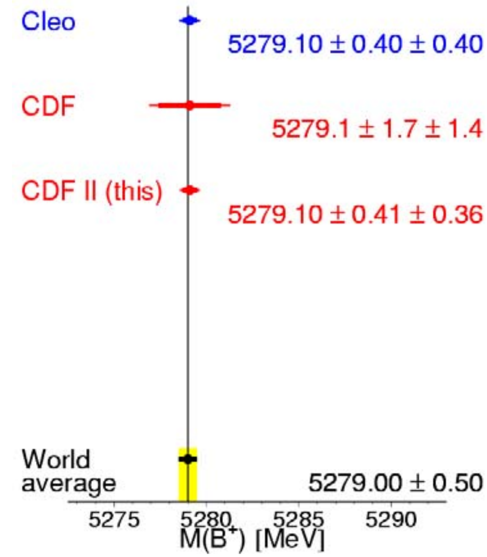
B_s mass



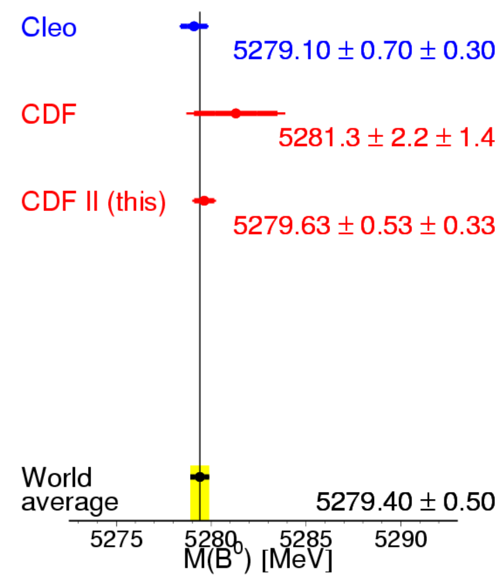
Λ_b mass



B^+



B^0



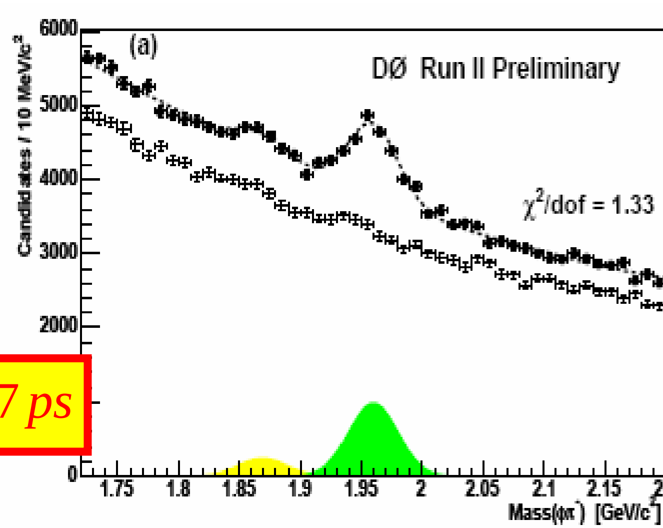
Systematics below 1 MeV for high statistics channels

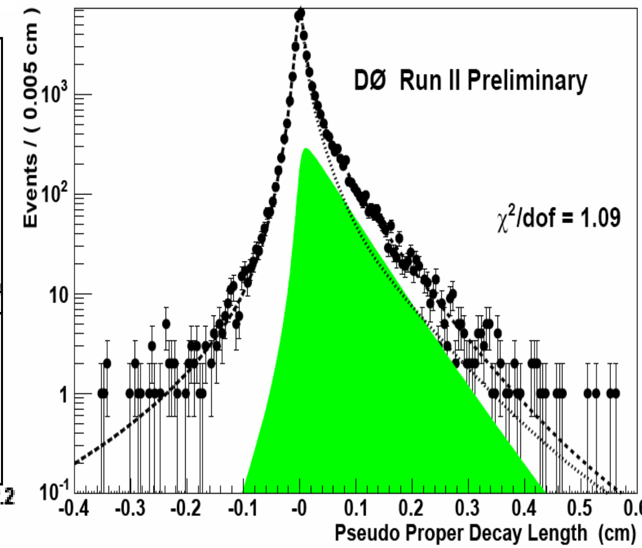
Best single measurements of *b*-hadron masses

Lifetime B_s

- DØ $B_s \rightarrow D_s l\, \upsilon$
  - $D_s \rightarrow \phi\pi$
  - Overcome υ w/simulation

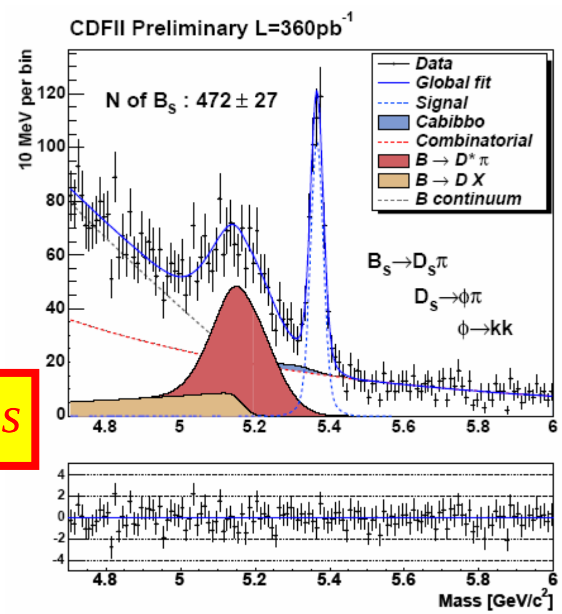
$$\tau(B_s) = 1.420 \pm 0.043 \pm 0.057\, ps$$

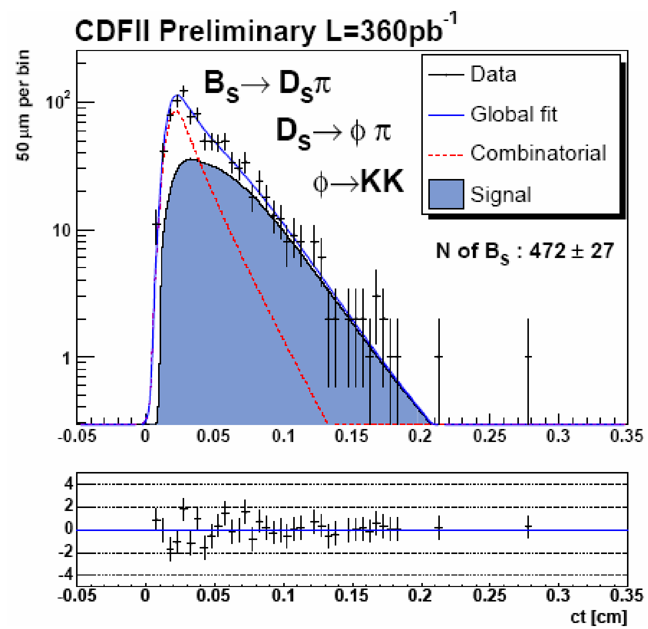




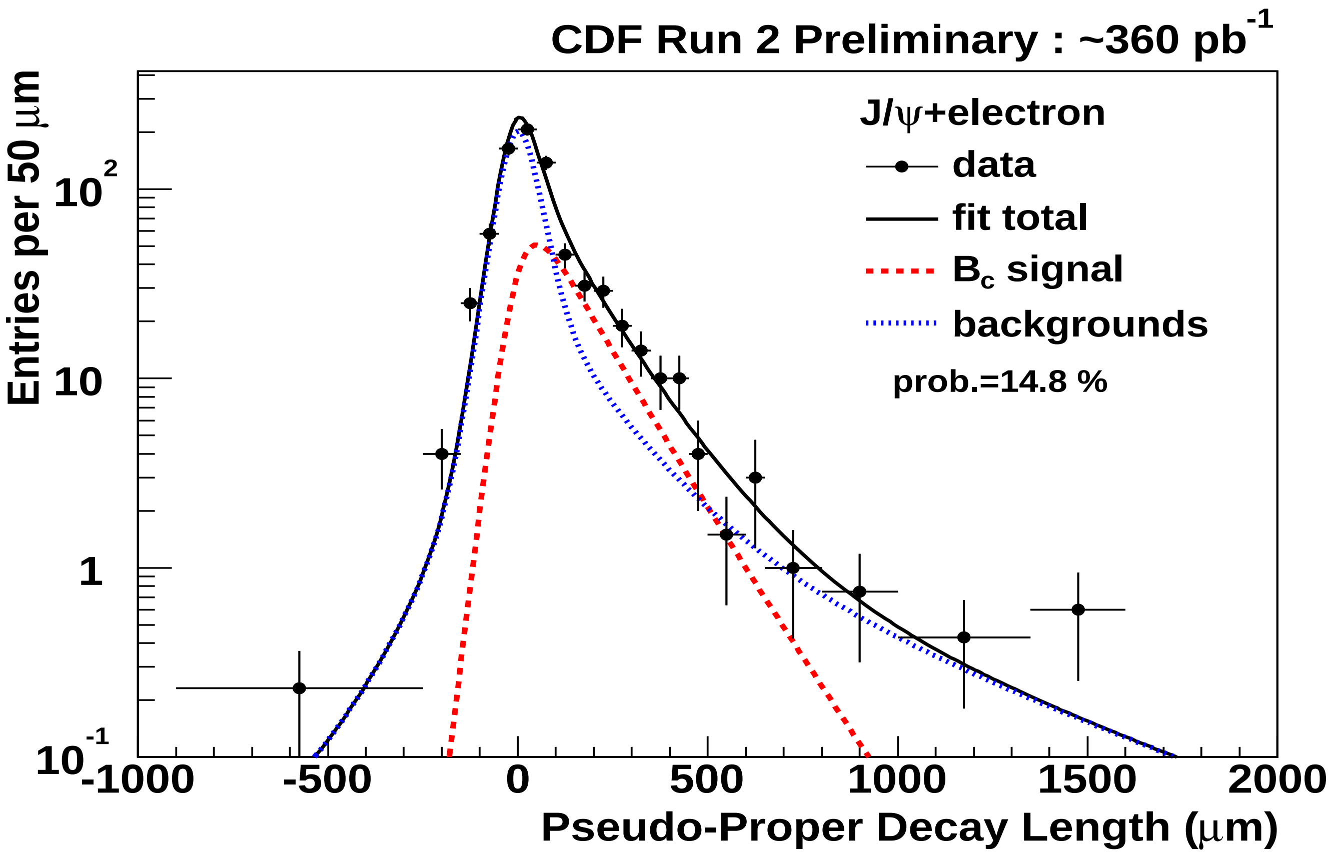
- CDF $B_s \rightarrow D_s\pi$
  - $D_s \rightarrow \phi\pi$
  - Trigger Bias

$$\tau(B_s) = 1.60 \pm 0.10 \pm 0.02\, ps$$



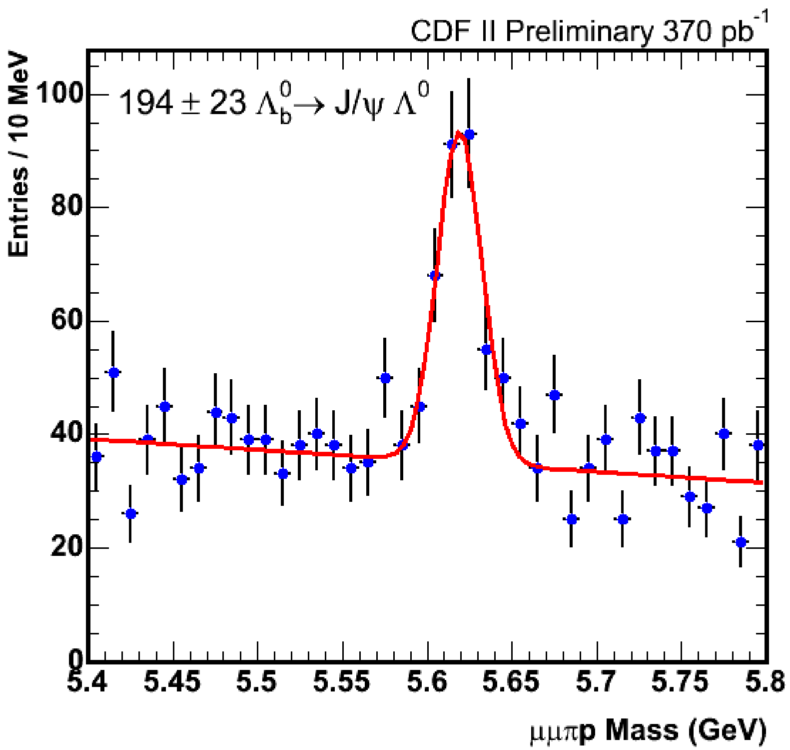


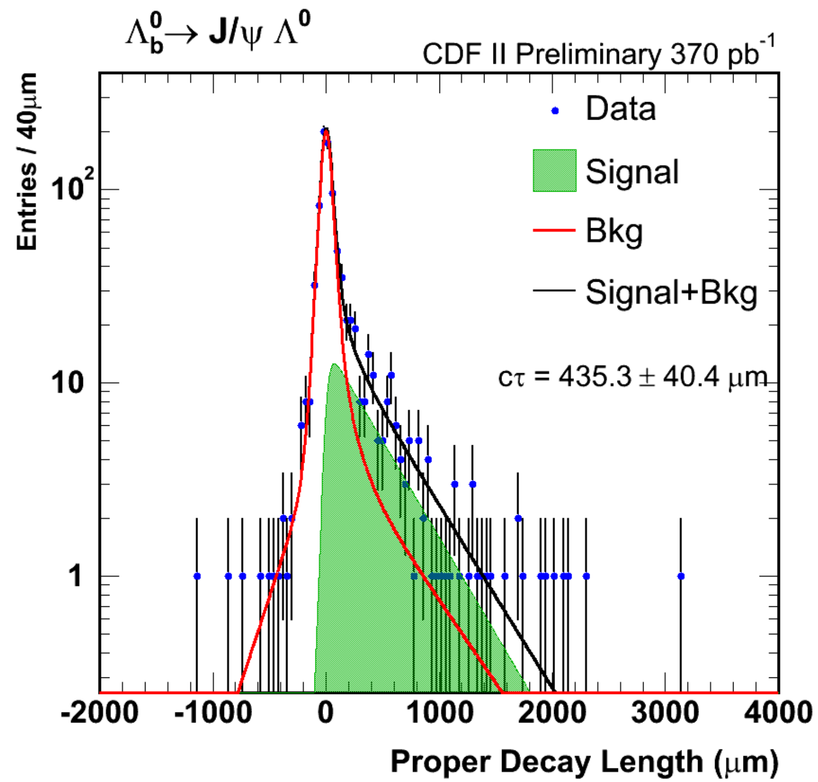
B_c Lifetime from J/ψ e (new)



$\tau(B_c)$ = 0.474 +0.074/-0.066(stat.) ± 0.033(syst) *ps*

Λ_b Lifetime (new)



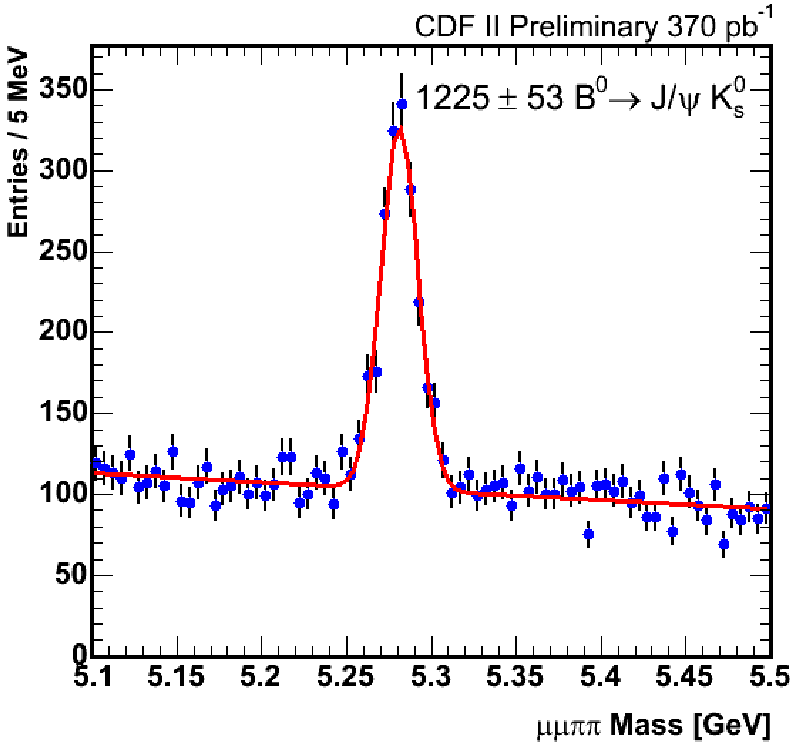


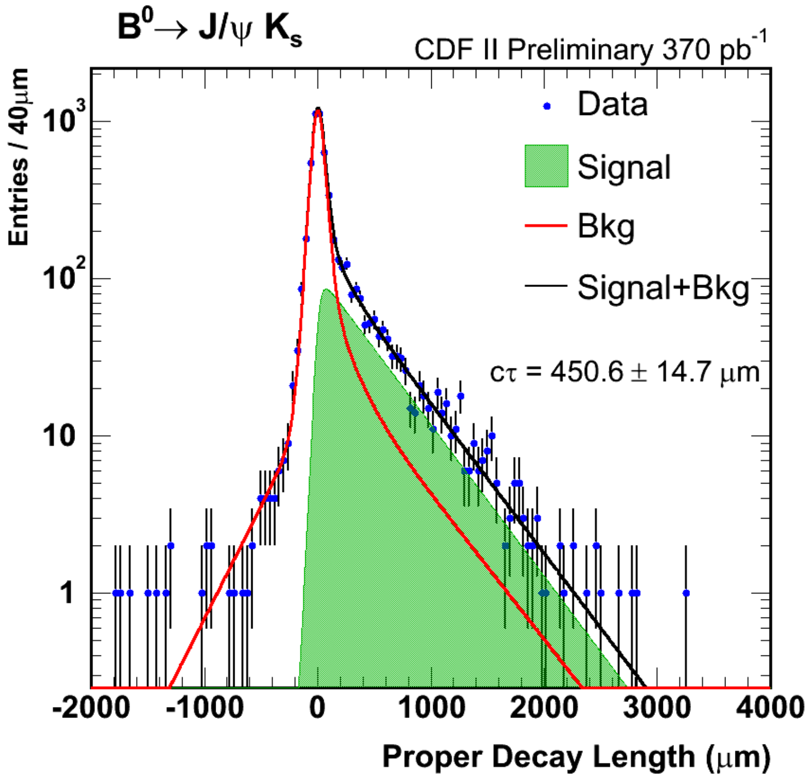
$\tau = 1.45 \pm 0.13(\text{stat}) \pm 0.02\ (\text{syst})$ ps

Within 1.4σ of world's measurement and 0.8σ of HQET

ALEPH (semi-leptonic) and CDF have similar precision

B^0 ($B \rightarrow J/\psi$ Ks) Lifetime





τ= 1.503 ± .05(stat) ± 0.016(syst) ps

B Lifetime Summary(CDF&D0)

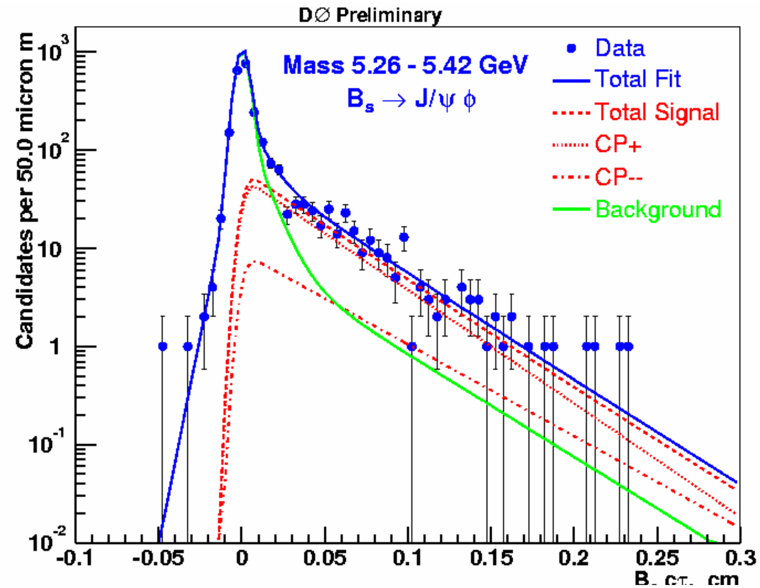
	Mode	CDF [ps]	DØ [ps]	HFAG 05
$\tau(B^+)$	J/ψ	1.662±0.033±0.008		1.653±0.010
	l υ	1.653±0.029 ±0.032		
	hadrons	1.66±0.03±0.01		
$\tau(B^0)$	J/ψ	1.539±0.051±0.008	1.473±0.051±0.023	1.528±0.009
	l υ	1.473±0.036±0.054	1.547±0.023±0.020±0.017†	
	hadrons	1.51±0.07±0.01		
$\tau(B_s)$	J/ψ	1.369±0.100±0.009	1.444±0.094 ±0.020	1.479±0.044
	l υ	1.383±0.055+0.052-0.046	1.420±0.043 ±0.057	
	hadrons	1.60±0.10±0.02		
$\tau(\Lambda_b)$	J/ψ	1.45±0.13±0.02	1.22+0.22-0.18 ±0.04	1.232±0.072

B^+ Belle 1.635 +/- 0.011+/-0.011

B^0 BaBar and Belle (Best) 1.534+/-0.008+/-0.010

B_s Lifetime Difference $\Delta\Gamma$

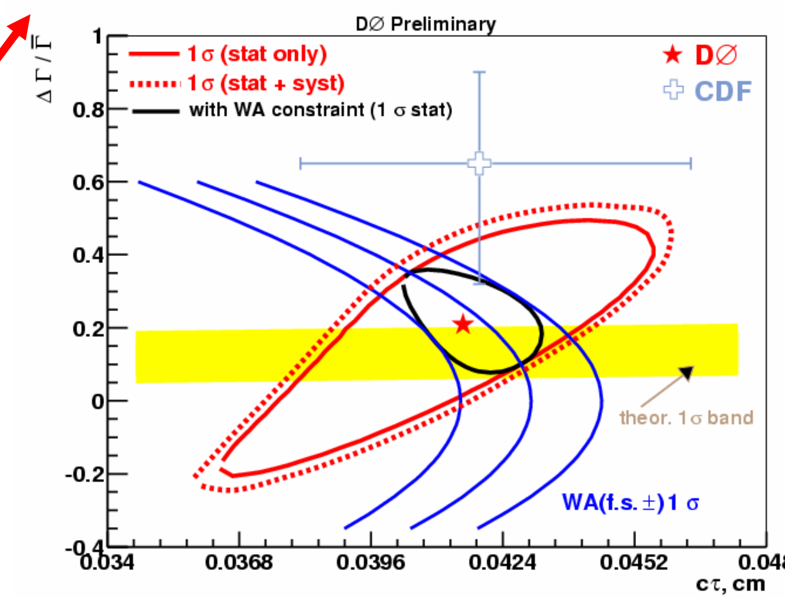
- $B_s \rightarrow J/\psi\phi$
  - *B* →VV, mixture of CP even/odd separate by angular analysis
  - Combine two-lifetime fit + angular→ $\Delta\Gamma_s = \Gamma_H - \Gamma_L$
  - SM $\Delta\Gamma_s/\Gamma_s = 0.12 \pm 0.06$ (Dunietz, Fleischer & Nierste)
- Indirect Measurement of Δm_s



$$\left.\frac{\Delta\Gamma_s}{\Delta m_s}\right|_{SM} = \left(3.7^{+0.8}_{-1.5}\right)\times 10^{-3}$$

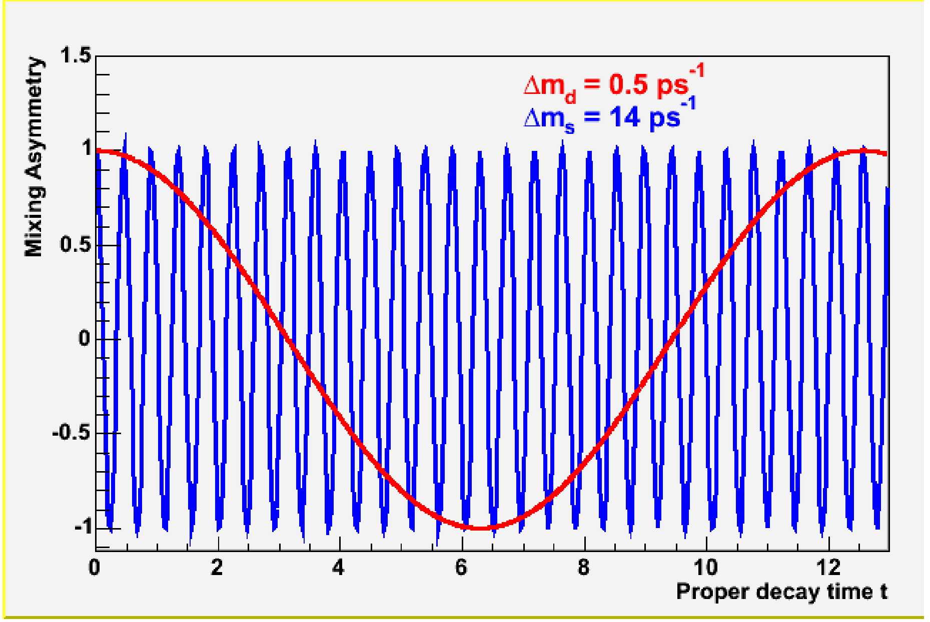
$$\frac{\Delta\Gamma}{\Gamma}\left(\text{DØ } 450\ pb^{-1}\right) = 0.21^{+0.33}_{-0.45}$$

$$\frac{\Delta\Gamma}{\Gamma}\left(\text{CDF } 240\ pb^{-1}\right) = 0.65^{+0.25}_{-0.33} \pm 0.01$$



B Mixing Measurement

- Measure Asymmetry
- Determine "time" of Decay:
- σ_t = Proper lifetime resolution
- Sort the mixed from unmixed via b charge at production and decay



$$A_{mix}(t) = \frac{N_{mix}(t) - N_{unmix}(t)}{N_{mix}(t) + N_{unmix}(t)} \propto \cos \Delta m t$$

$$\mathrm{Re}(V_{ts}) \approx 0.040 > \mathrm{Re}(V_{td}) \approx 0.007$$

$$\mathrm{Sig}(\Delta m) = \sqrt{\frac{S}{S+B}}\, e^{-(\Delta m \sigma_t)^2/2} \sqrt{\frac{S \varepsilon D^2}{2}}$$

1) Signal/noise

2) vertex resolution or time resolution

3) tagging efficiency and Dilution

Calibration Flavor Tagging on B_d

- Know the right answer
  - Tests Fitting Mechanism
  - Calibrates Tagging
  - Much higher statistics

CDF

$\Delta m_d = 0.503 \pm 0.063 \pm 0.015\ ps^{-1}$

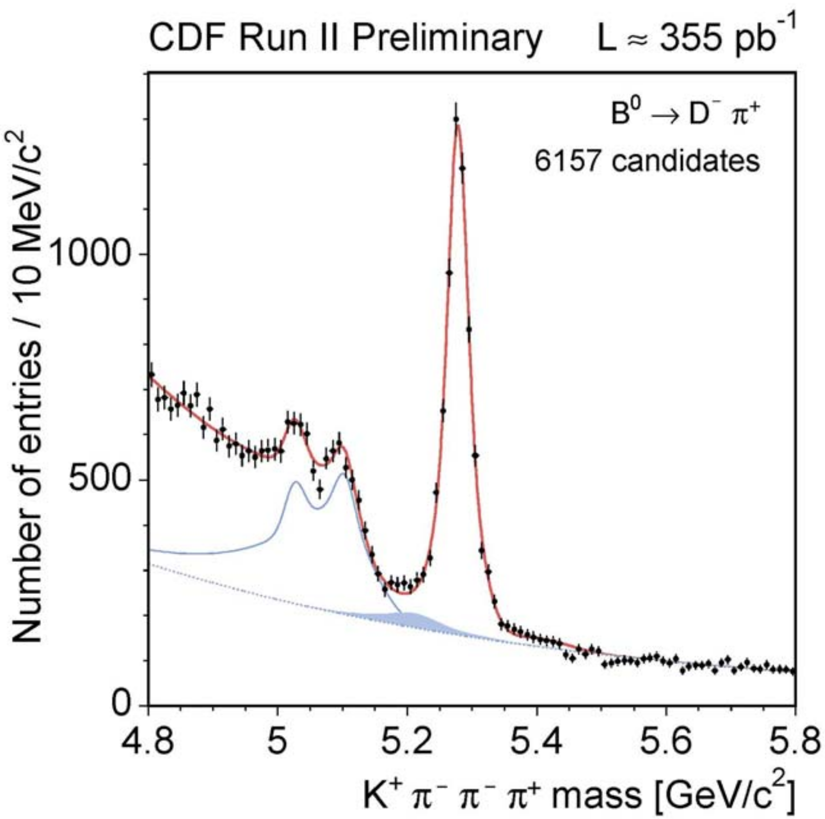
$\varepsilon D^2 = 1.55 \pm 0.16 \pm 0.05\%$

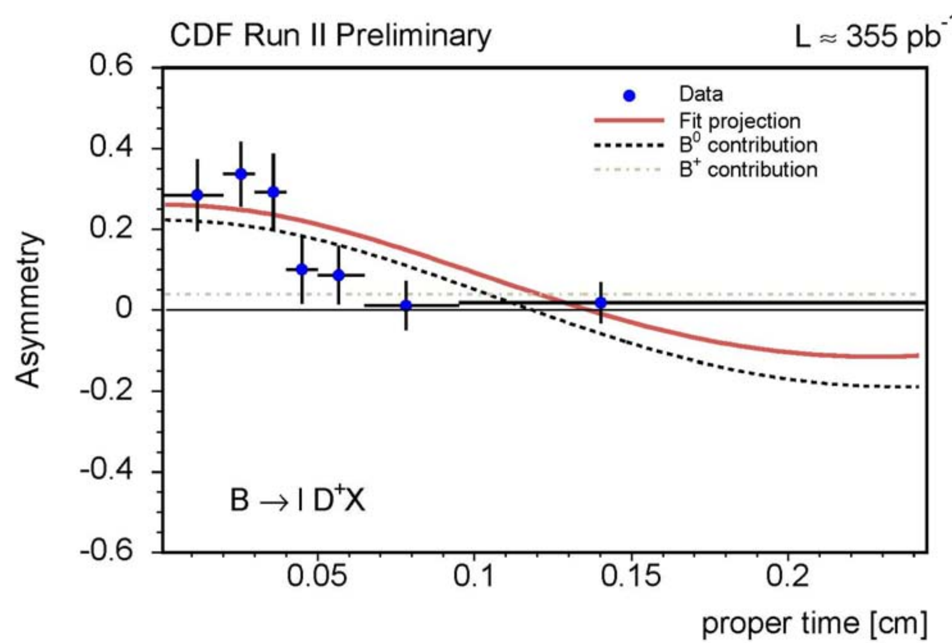
D0

$\Delta m_d = 0.558 \pm 0.048\ ps^{-1}$

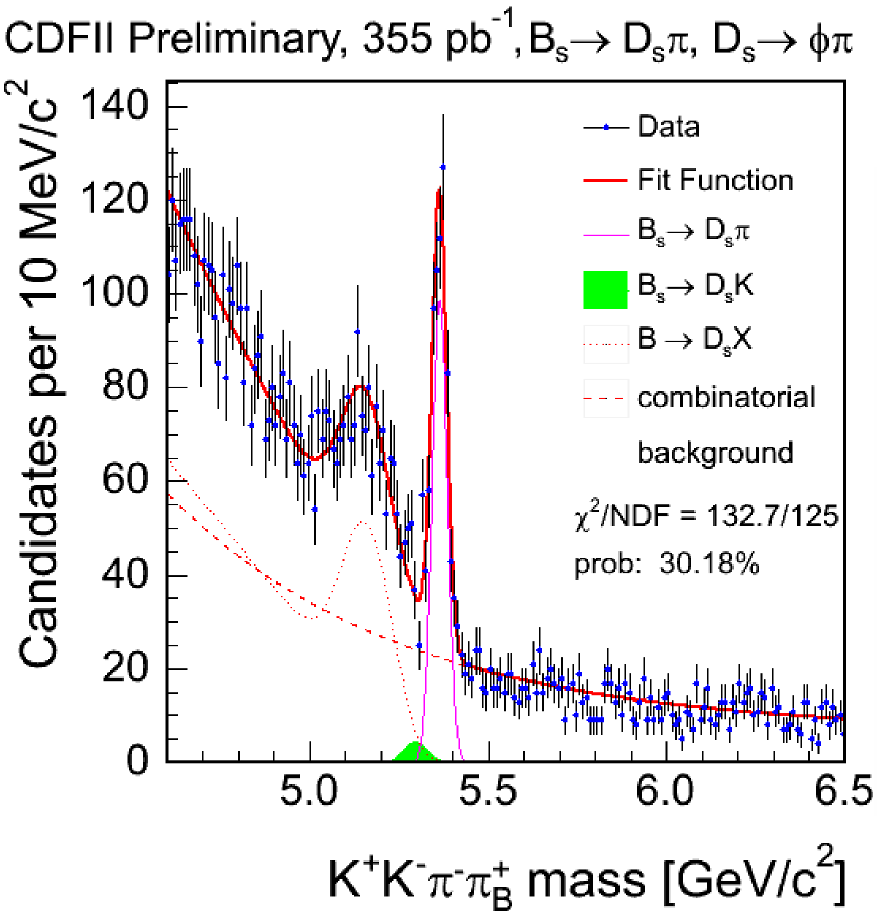
$\varepsilon D^2 = 1.16 \pm 0.16\%$

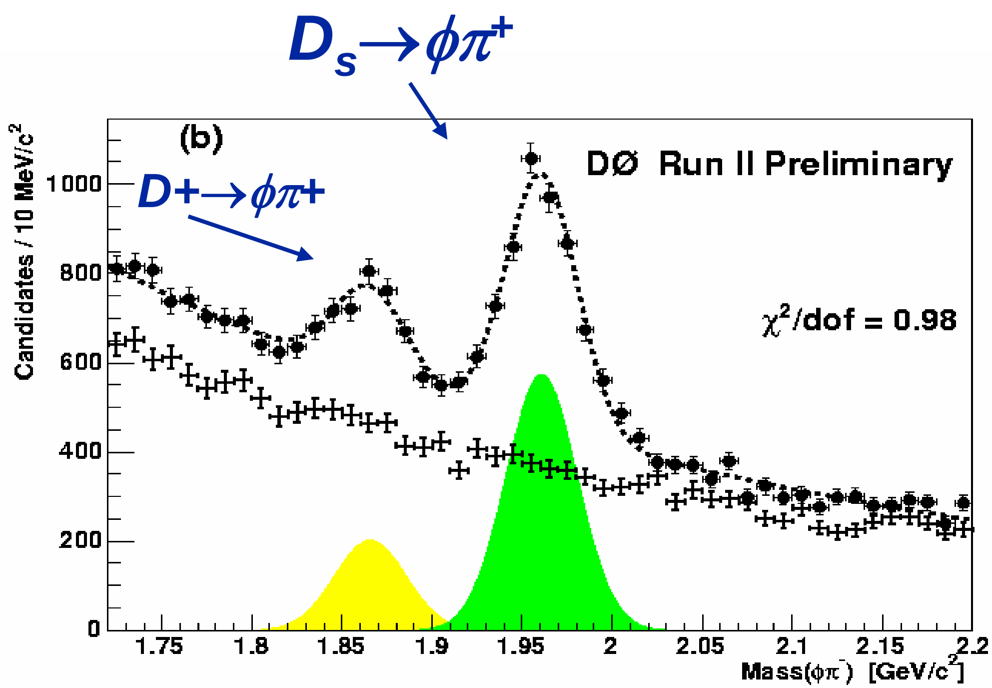
$\Delta m_d = 0.510 \pm 0.006\ ps^{-1}$ (HFAG Winter05)





Golden B_s Mixing Decay Modes



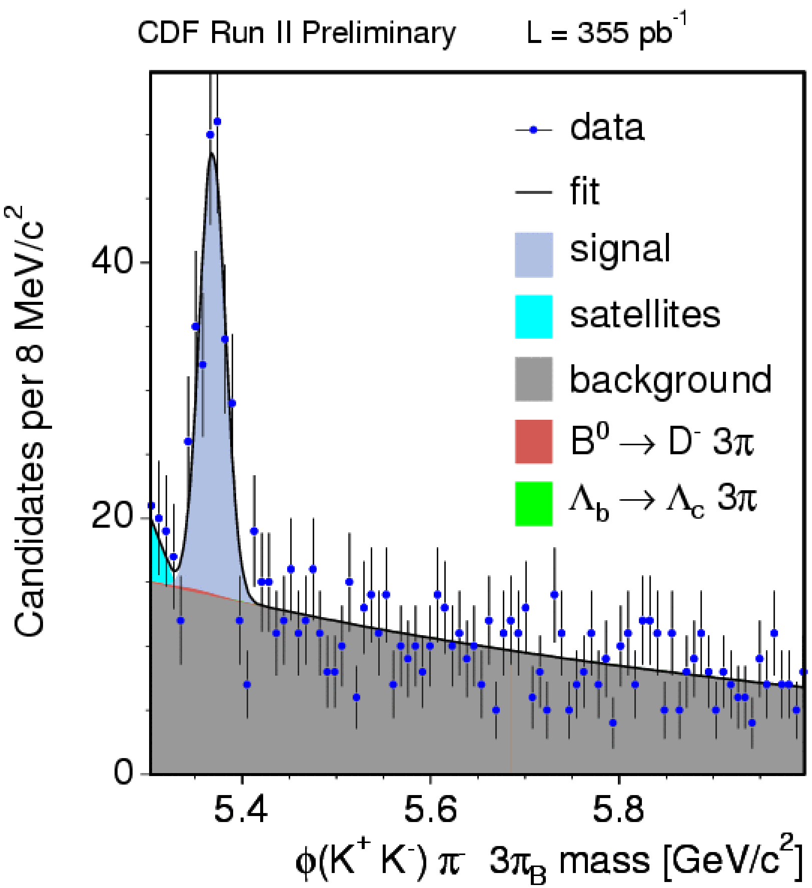


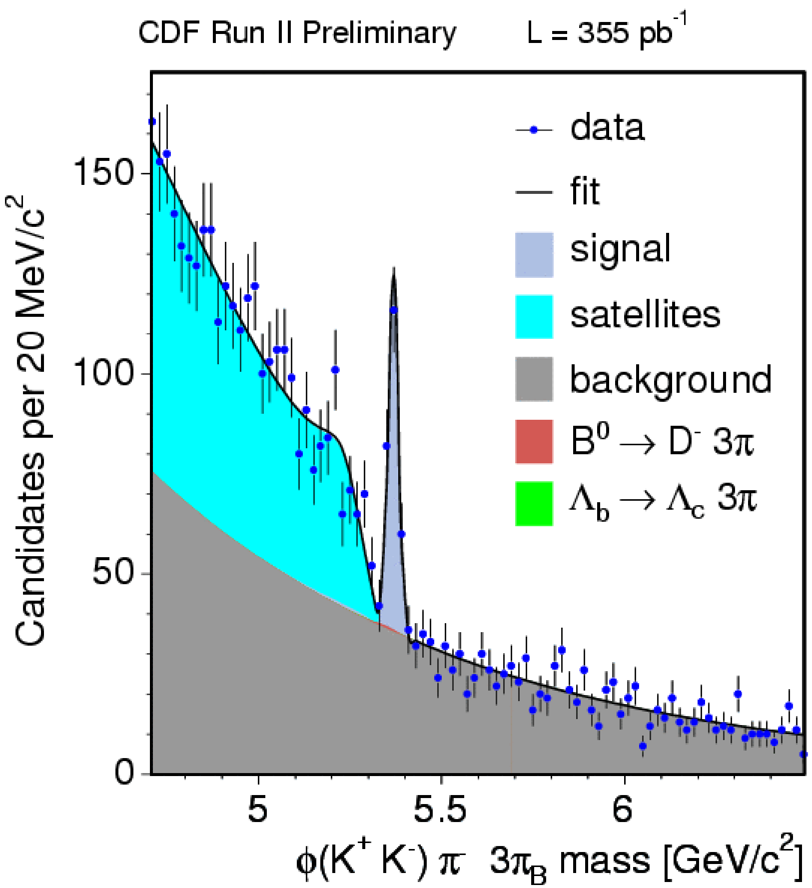
Fully hadronic mode only possible because of CDF Vertex Trigger-critical for large mixing

Silicon Vertex Trigger is a major technical advance

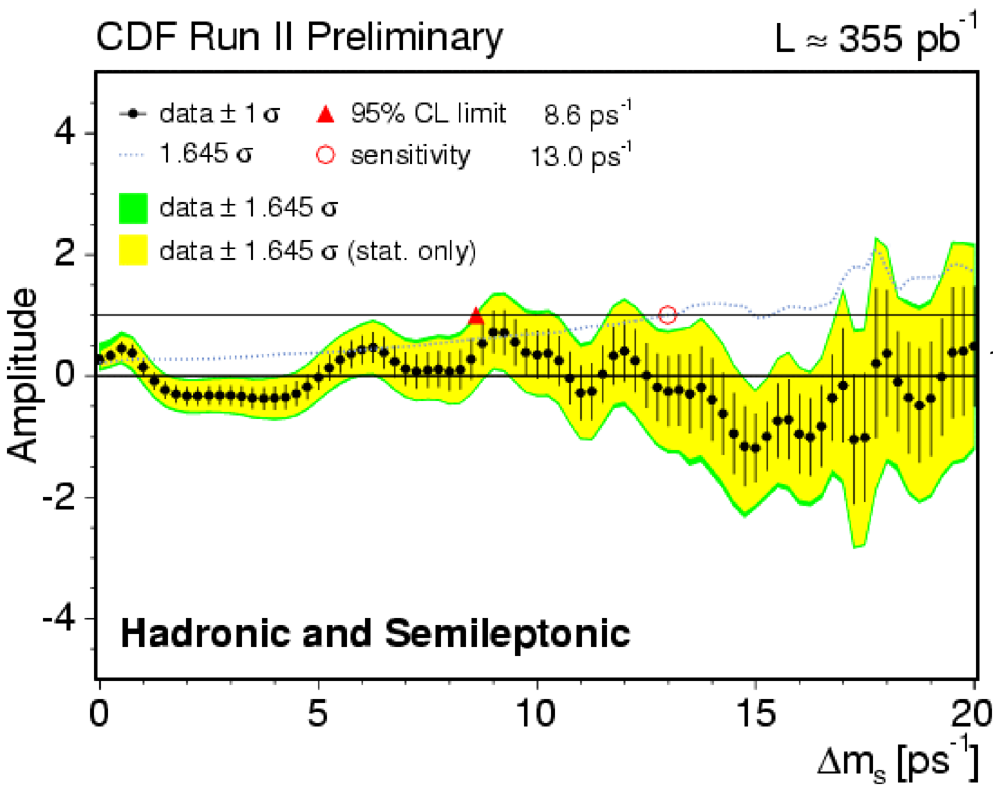
New Additional Bs Mixing Mode (CDF)

$B_s \rightarrow D_s\ 3\pi\ (D_s \rightarrow \phi\pi,\ K^{*0} K^{-})$





New Bs Mixing Amplitude Scan Result



$$\mathcal{L}_t \propto \left(1 + A \cdot D\cos\left(\Delta m t\right)\right)$$

NIM
A384(1997)
p.491-505

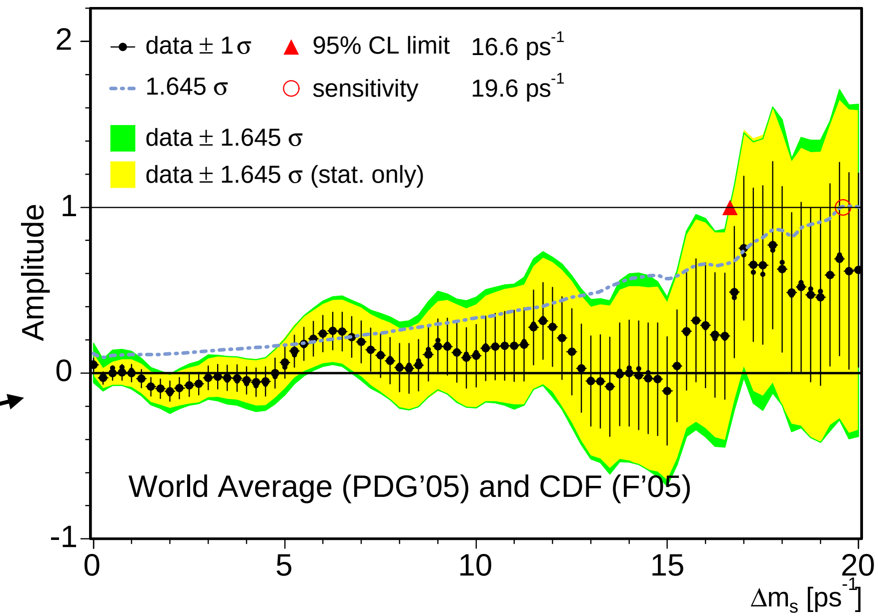
Amplitude Scan

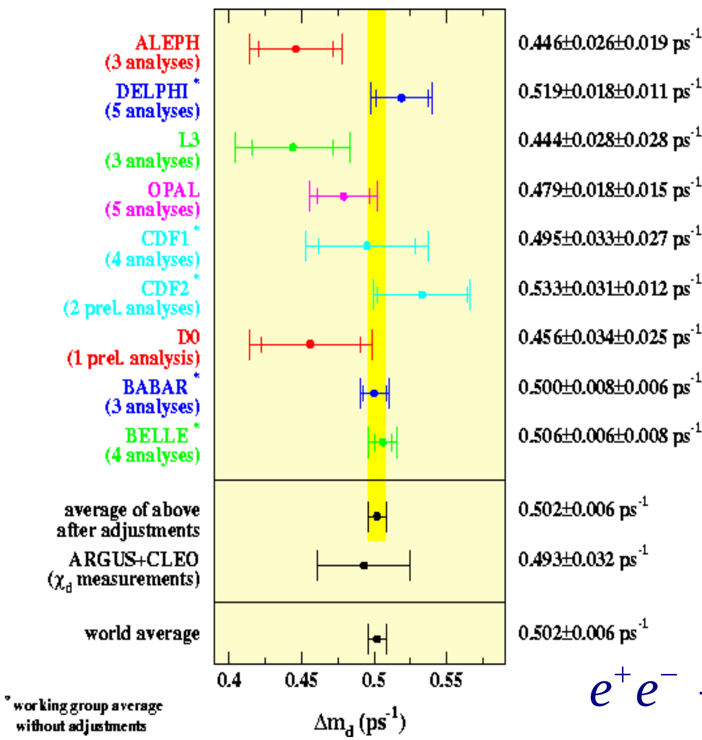
Fourier Transform into Δm space
only floating A
A = 1 for true Δm, 0 else
Limit ≡ $A + 1.645\sigma_A = 1$
Sensitivity ≡ $1.645\sigma_A = 1$
NIM A384(1997) p.491 ff.

- Use ~1100 fully reconstructed B_s decays

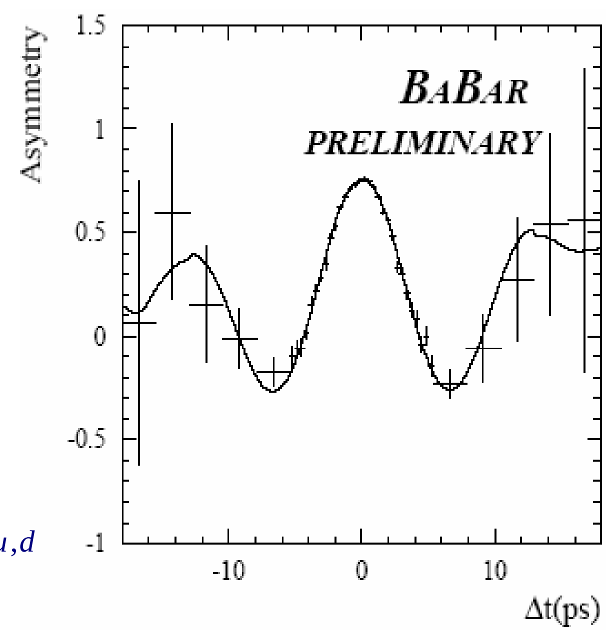
Current World B Mixing Knowledge

- Δm_d dominated by “B factories”
  - Designed specifically for this purpose
- Δm_s not accessible at B factories, have world ave. $e^+e^- \to Z \to b\bar{b}$
  - Limit from $p\bar{p} \to b\bar{b}X$ and





$$e^+e^- \to \Upsilon(4S) \to B_{u,d}\bar{B}_{u,d}$$

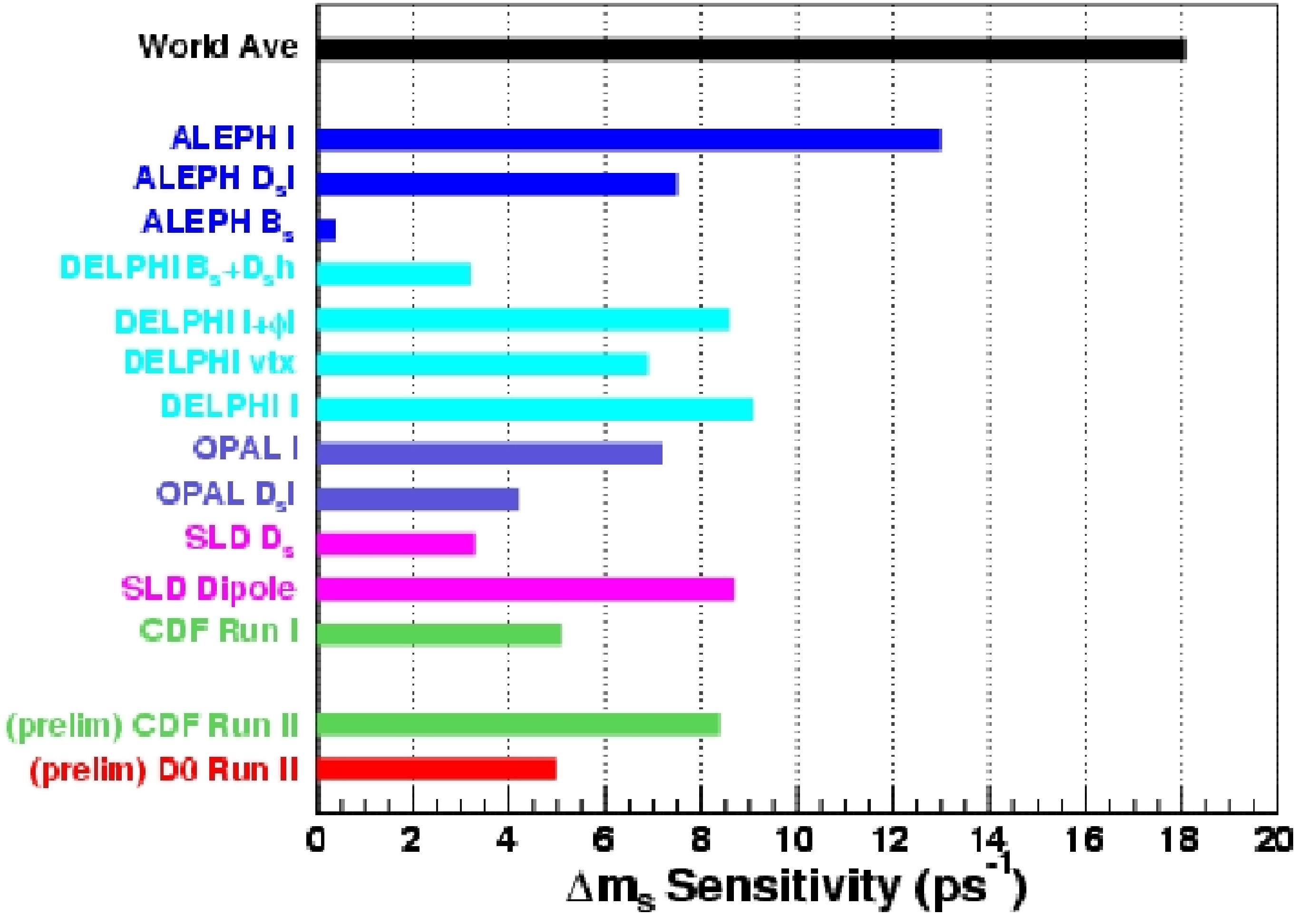


B_s Mixing Results Summary

Source	Δm_s > (95%)	Sensitivity
DØ $D_s l\nu$	5.0 ps^{-1}	4.6 ps^{-1}
CDF $D_s l\nu$	6.7 ps^{-1}	10.4 ps^{-1}
CDF $D_s\pi$	0.0 ps^{-1}	9.8 ps^{-1}
CDF Comb.	8.6 ps^{-1}	13.0 ps^{-1}
PDG 04	14.5 ps^{-1}	18.1 ps^{-1}
PDG 05⊕CDF05	16.6 ps^{-1}	19.6 ps^{-1}

CDF B_s mixing measurement has significant impact on world limit

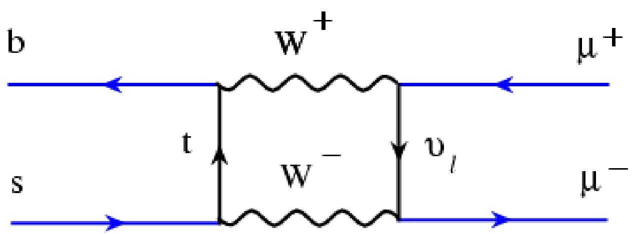
B_s Sensitivity (LP05)

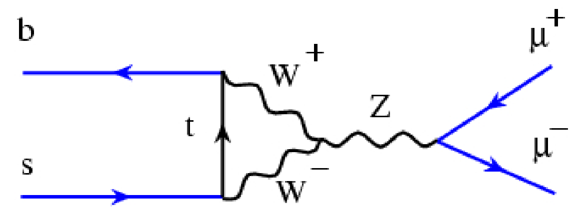


$$B^0_{d,s} \to \mu^+\mu^-$$

BR($B_s \to \mu\mu$): Why are FCNC interesting?

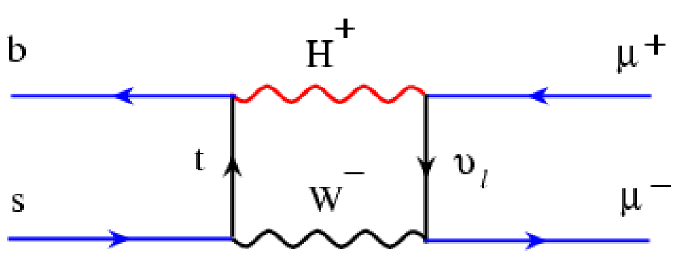
- BR($B_s \to \mu\mu$) in the SM is $$BR(B_s \to \mu^+\mu^-) = (3.4 \pm 0.5) \times 10^{-9}$$

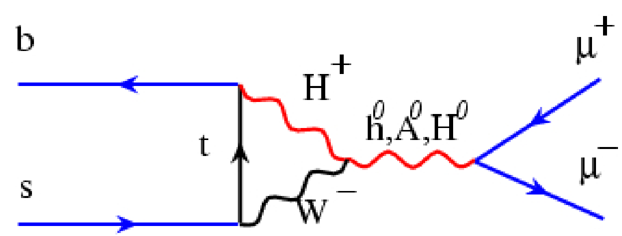




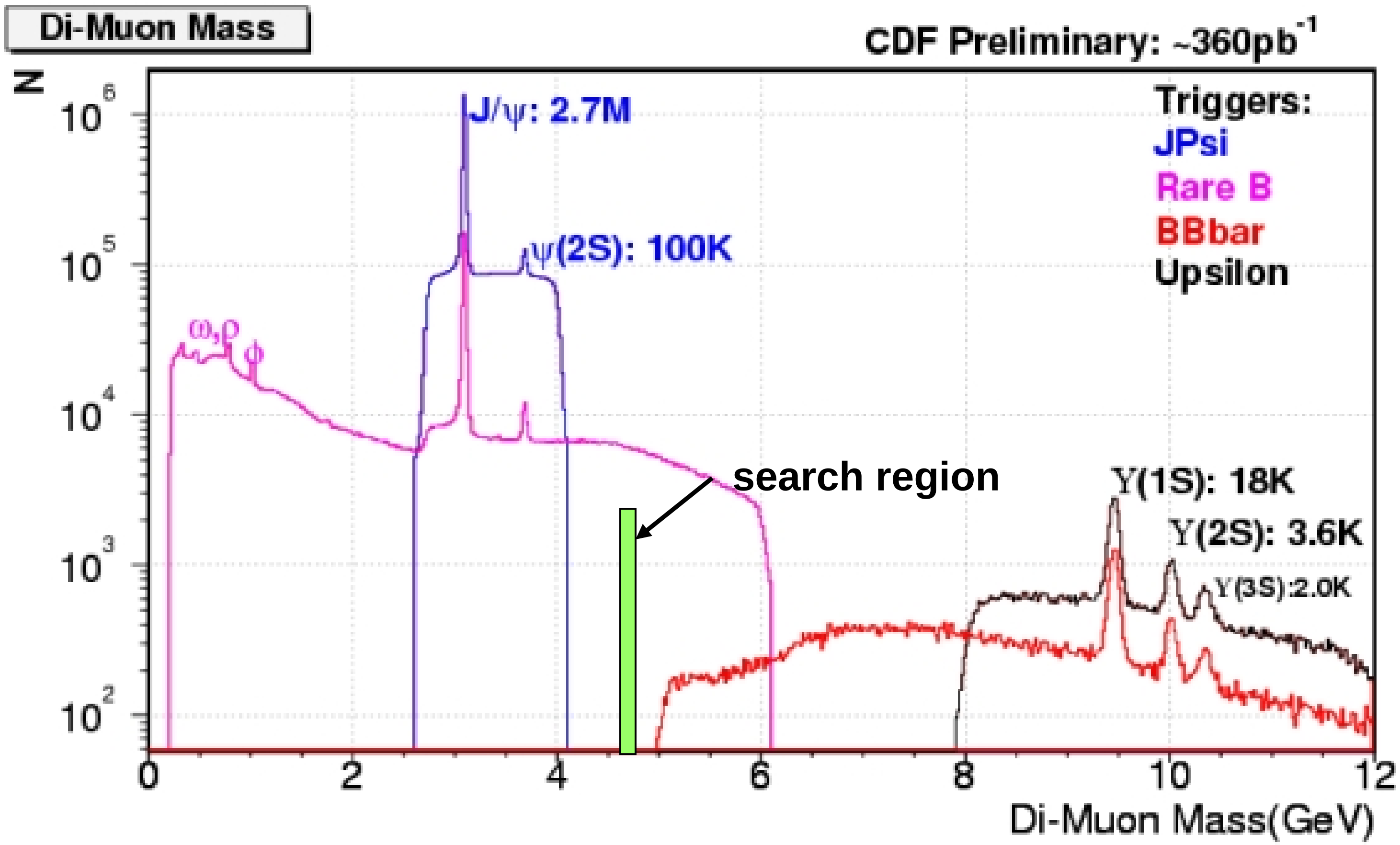
A. Buras Phys. Lett. B 566,115

- Can be enhanced by 10-100 in SUSY
  - Consistent with Δa_μ, and Ω_{cdm}
  - Observable with ~2 fb-1
  - Would imply light Higgs M_h~120 GeV



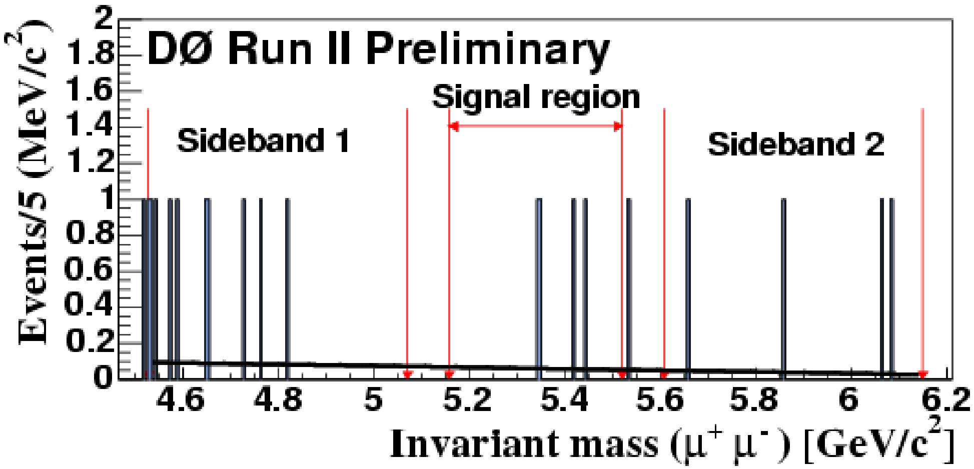


Di-muon mass Spectrum at CDF



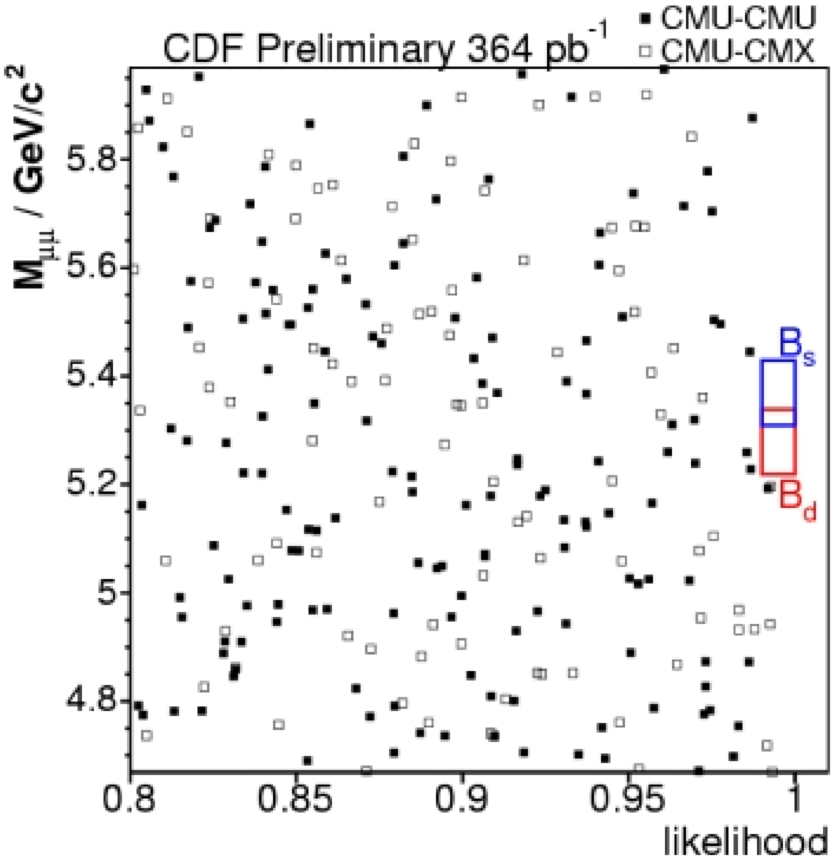
Results

D0



- Expected background: 4.3 ± 1.2
- Observed: 4

CDF



- Expected background: 1.5 ± 0.2
- Observed: 0

CDF and D0 Combined:

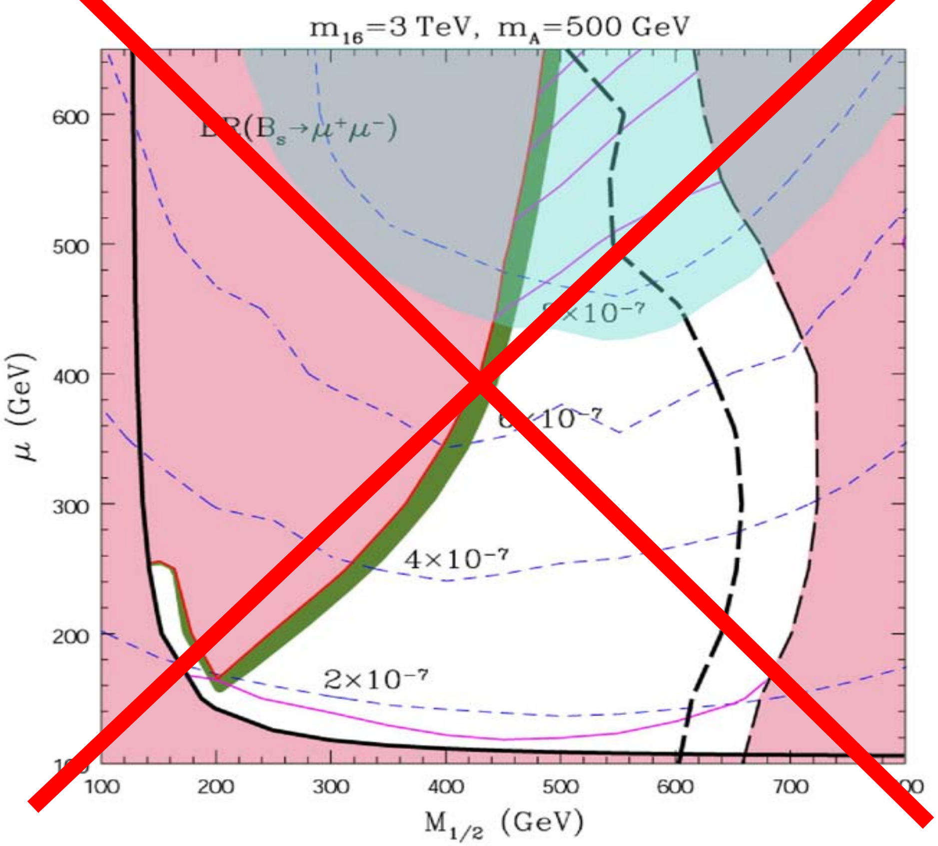
BR($B_s \rightarrow \mu\mu$) < 1.2×10^{-7} @ 90% CL
< 1.5×10^{-7} @ 95% CL

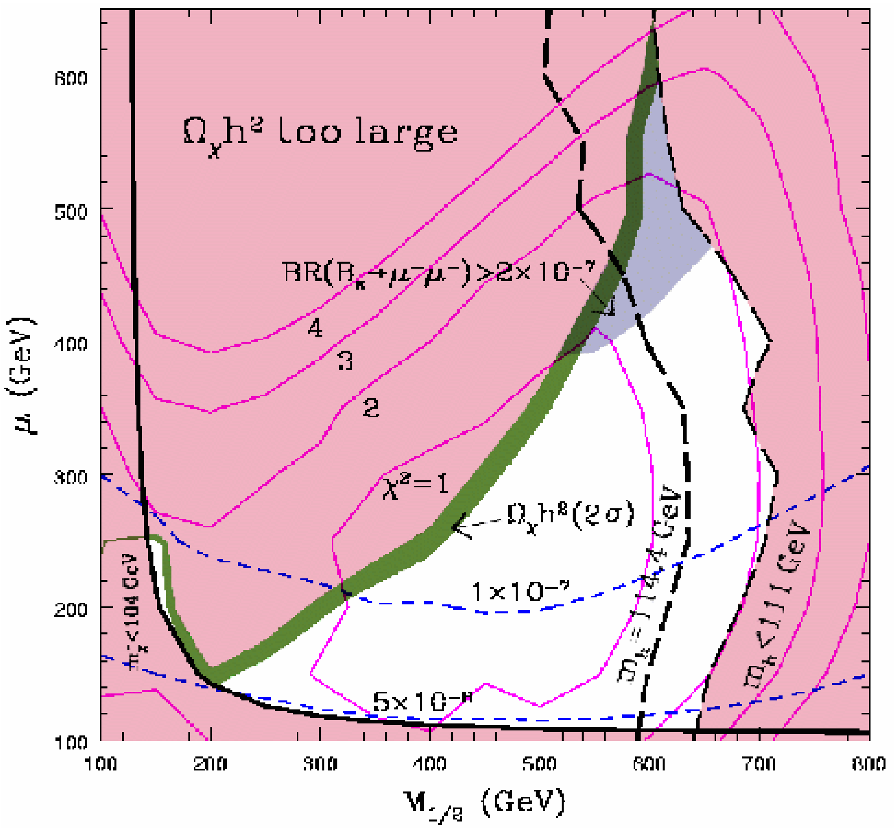
BR($B_d \rightarrow \mu\mu$) < 3.2×10^{-8} @ 90% CL
< 4.0×10^{-8} @ 95% CL

MSSM with Minimal SO(10) Soft SUSY Breaking

R. Dermisek *et al.*, JHEP 0304 (2003) 037

R. Dermisek *et al.*, hep-ph/0507233 (2005)





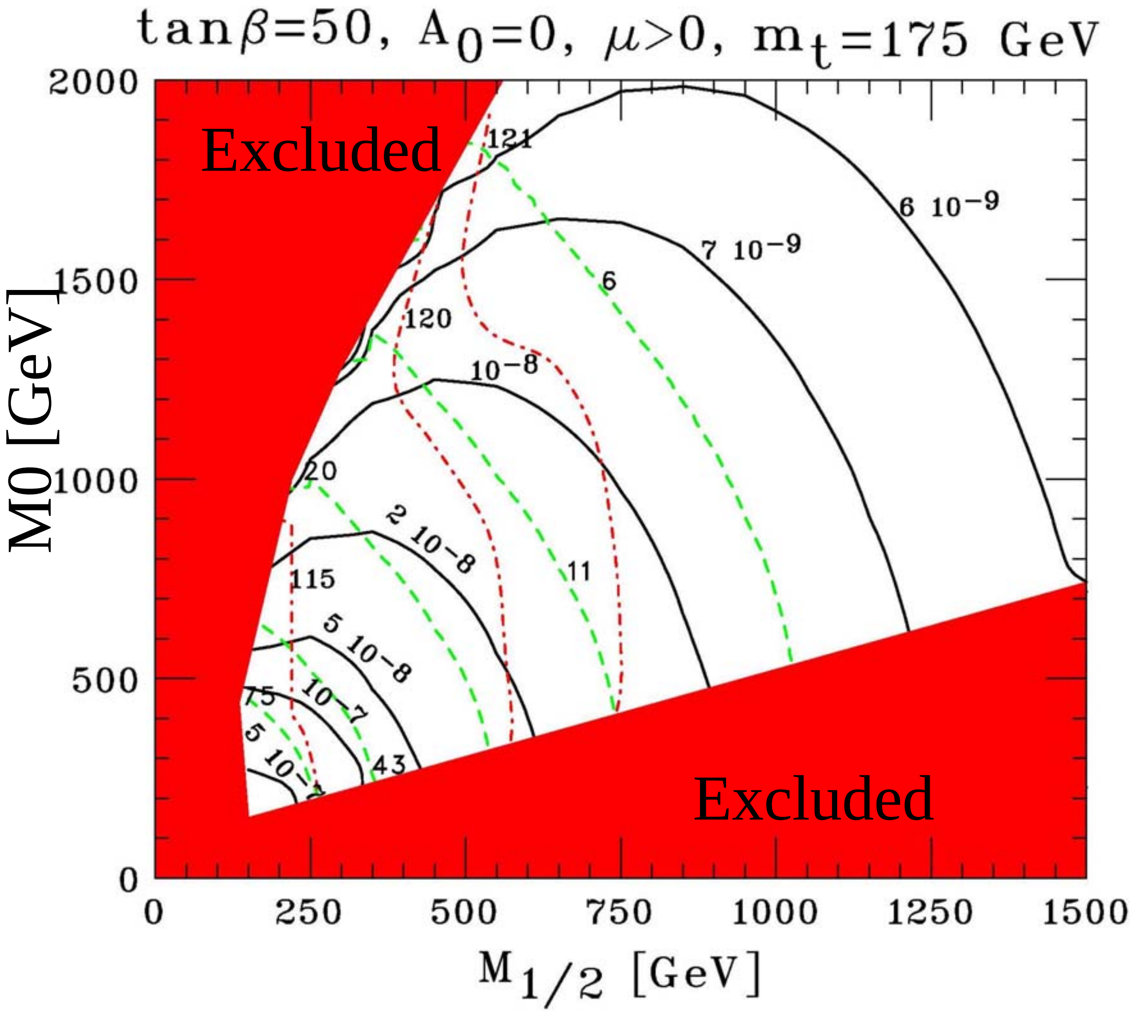
Red regions are excluded by either theory or experiments
Green region is the WMAP preferred region
Blue dashed line is the Br(Bs→μμ) contour
Light blue region excluded by Bs→μμ analysis

tan(β)~50 constrained by unification of Yukawa couplings

mSUGRA M0 vs $M_{1/2}$

Dedes, Dreiner, Nierste,
PRL 87(2001) 251804

- For m_h~115GeV implies $10^{-8}<Br(B_s \rightarrow \mu\mu)<3\times10^{-7}$



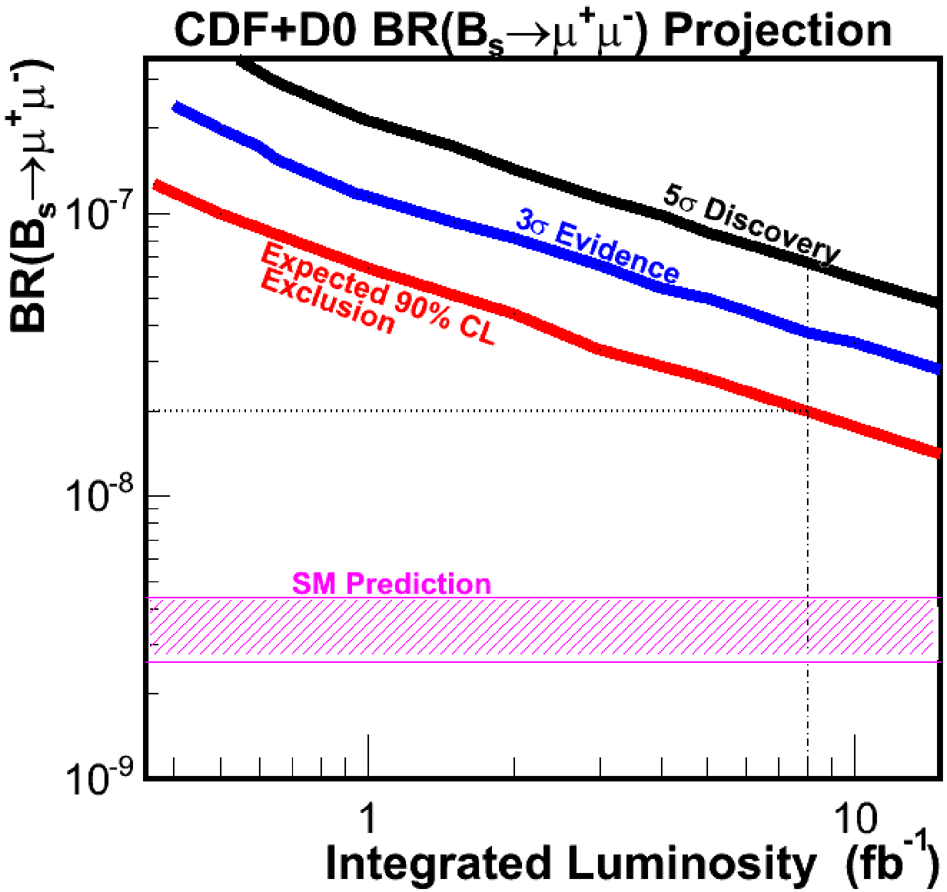
Solid red = excluded by theory or experiment

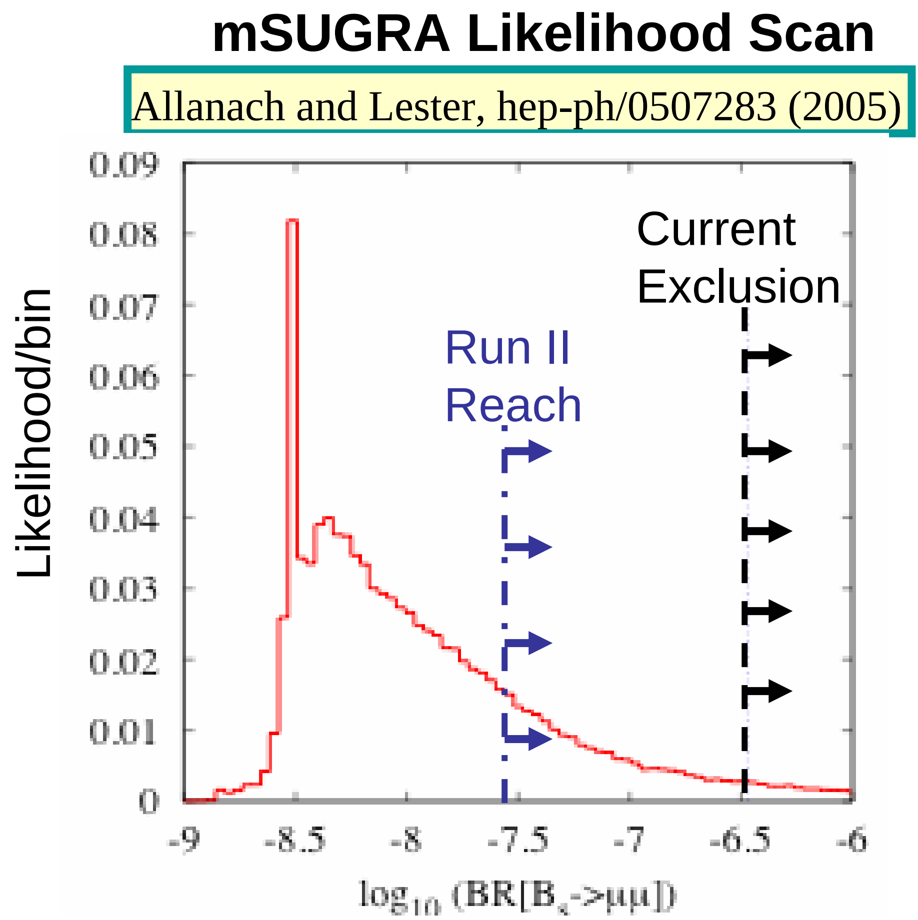
Dashed red line = light Higgs mass (m_h)

Dashed green line = (δa_μ)susy (in units of 10^{-10})

Black line = $Br(B_s \rightarrow \mu\mu)$

TEVATRON REACH on $B_s \rightarrow \mu\mu$



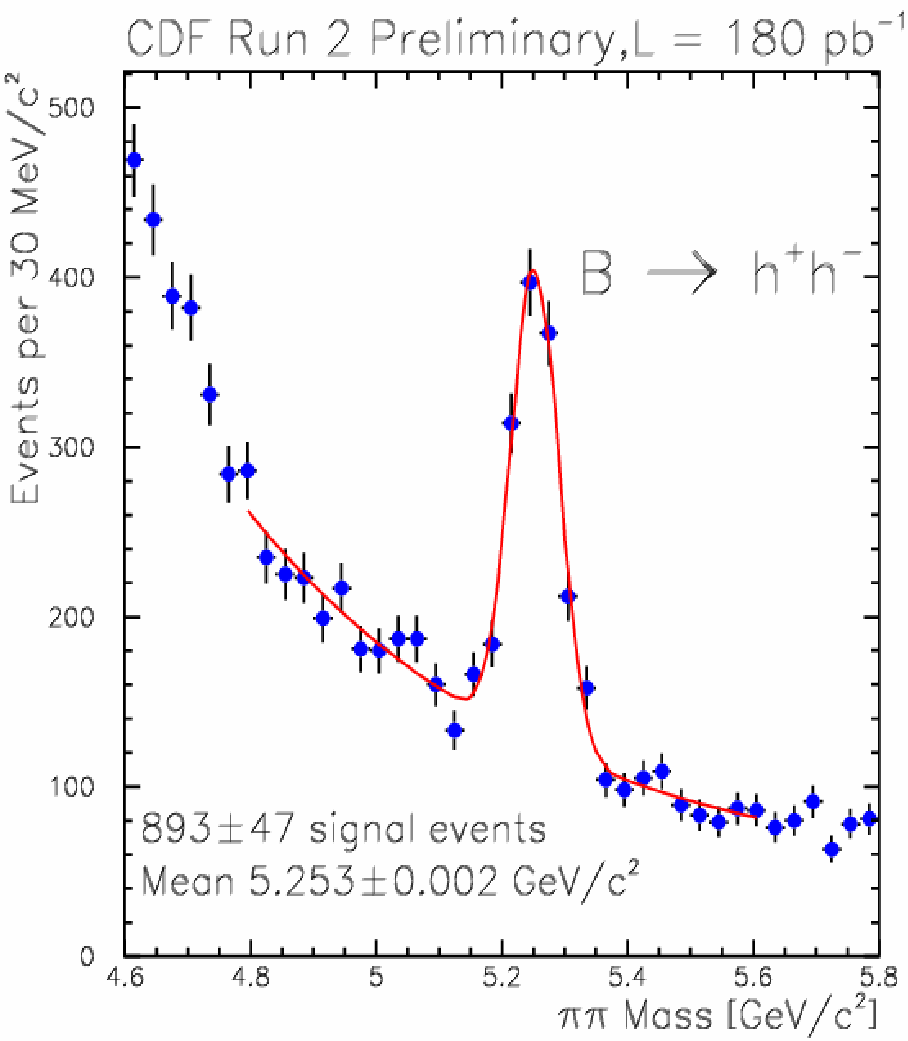


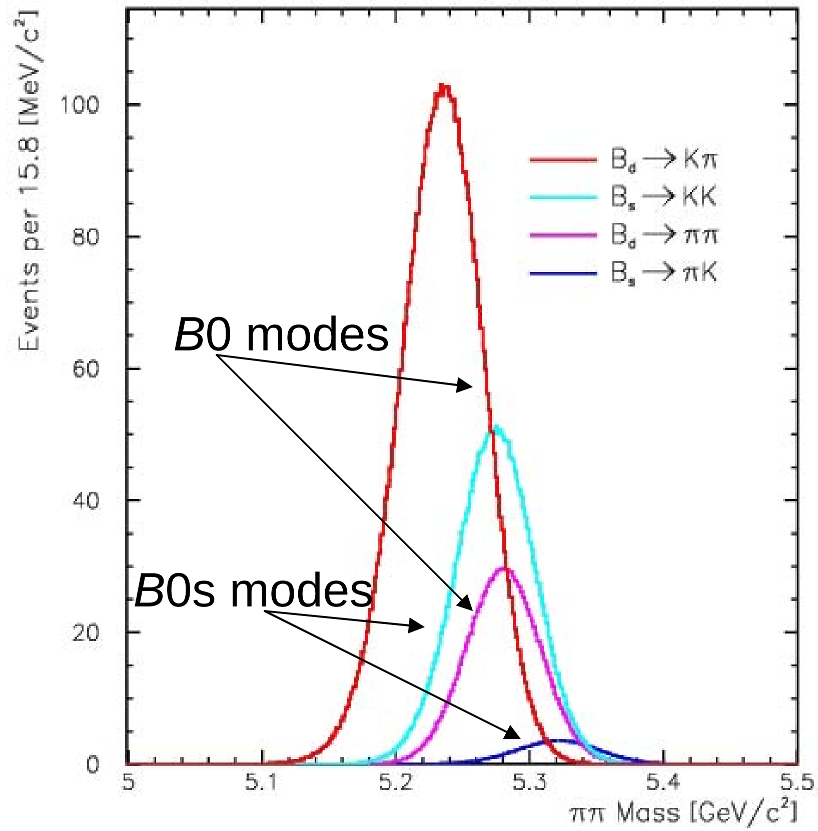
- Can push down to low 10^{-8} region
- Modest improvement in sensitivity expected with new analyses

- Run II can exclude ~30% of currently allowed mSUGRA phase space

$$B^0_{d,s} \rightarrow h^+h^-$$

B→ h⁺h⁻

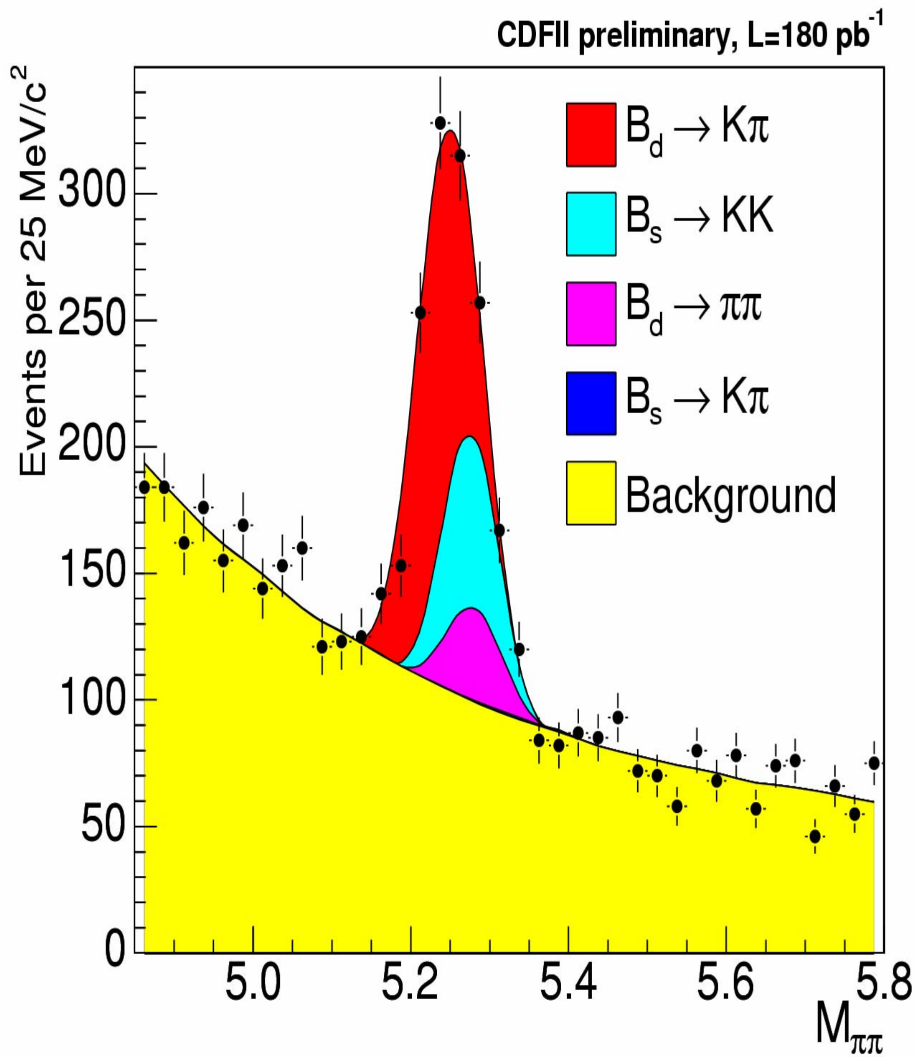




Challenge is to separate signals

Use dE/dx from drift chamber

Results



parameter	fraction	yield
$B^0 \to \pi^+\pi^-$	$(13 \pm 3)\%$	121 ± 27
$B^0 \to K^+\pi^-$	$(60 \pm 3)\%$	542 ± 30
$B_s^0 \to K^-\pi^+$	$(0 \pm 3)\%$	-
$B_s^0 \to K^+K^-$	$(26 \pm 3)\%$	236 ± 32

~900 evts/180 pb-1 in initial CDF data, taken with still non optimized detector/trigger. Now much better: ~2700 / 360 pb-1

Final results: B^0_s sector

$$\frac{f_s \cdot BR(B^0_s \to K^+K^-)}{f_d \cdot BR(B^0 \to K^+\pi^-)} = 0.46 \pm 0.08\ (stat.) \pm 0.07\ (syst.)$$

$B^0_s \to K^+K^-$ decay established. BR ratio may favor large SU(3) breaking as predicted from sum rules (Khodjamirian et al. PRD68:114007, 2003).

$$\frac{f_d \cdot BR(B^0 \to \pi^+\pi^-)}{f_s \cdot BR(B^0_s \to K^+K^-)} = 0.45 \pm 0.13\ (stat.) \pm 0.06\ (syst.)$$

Allows first comparisons with *Y(4S)* and theory expectations, test of NP.

$$\frac{f_s \cdot BR(B^0_s \to K^-\pi^+)}{f_d \cdot BR(B^0 \to K^+\pi^-)} < 0.08 \text{ @ } 90\%\ C.L.$$

No evidence for $B^0_s \to K^-\pi$, set a limit a factor ~40 better than PDG04.

$$\frac{BR(B^0_s \to \pi^+\pi^-)}{BR(B^0_s \to K^+K^-)} < 0.05 \text{ @ } 90\%\ C.L.$$

Great improvement on annihilation mode $B^0_s \to \pi\pi$. A factor >100 below PDG04 (time-evolutions of $B^0_s \to \pi\pi$ and $B^0_s \to K^-K^+$ assumed the same).

Final results: B^0 sector

$$A_{\mathrm{CP}} = \frac{N(\overline{B}^0 \to K^-\pi^+) - N(B^0 \to K^+\pi^-)}{N(\overline{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)} \quad = \quad -0.013 \pm 0.078\ (stat.) \pm 0.012\ (syst.)$$

A_{CP} compatible with *B*-factories, systematic uncertainty comparable as well, Babar statistic uncertainty ~30% better. With currently available data (3x statistics), we expect < 4.5% statistical uncertainty to be compared with current world best: 2.2% (Belle).

$$\frac{BR(B^0 \to K^+K^-)}{BR(B^0 \to K^+\pi^-)} \quad < \quad 0.10 \ @\ 90\%\ C.L.$$

Limit on pure annihilation/exchange mode $B^0 \to K^+K^-$. A factor ~2 above *B*-factories, expect much better performance on current sample.

$$\frac{BR(B^0 \to \pi^+\pi^-)}{BR(B^0 \to K^+\pi^-)} \quad = \quad 0.21 \pm 0.05\ (stat.) \pm 0.03\ (syst.)$$

Consistent with *B*-factories. Valuable cross-check for other measurements.

Conclusions

- B Physics from Tevatron already impressive
- An order of magnitude more data before completion

- Looking forward to being main contributor to B_s limit and hopefully a measurement is possible (major effort)
- Studies of very large samples of $B \to hh$ modes including CP (angle γ)
- Pushing limits of $B \to \mu\mu$ τo $\sim$ a few 10^{-8} (powerful probe of new physics)

Acknowledgements

- Thanks especially to:

- Cheng-Ju Stephen Lin ($B \to \mu\mu$)
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- Matt Herndon convener
- Christoph Paus Bs Mixing
- Ilya Kravchenko Bs Mixing
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